MONTHLY WEATHER REVIEW

VOLUME 83 NUMBER 12

DECEMBER 1955

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U. S. DEPARTMENT OF COMMERCE • WEATHER BUREAU

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As the national meteorological service for the United States, the Weather Bureau issues several periodicals, serials, and miscellaneous publications on weather, climate, and meteorological science as required to carry out its public service functions. The principal periodicals and serials are described on this page and on the inside of the back cover. A more complete listing of Weather Bureau publications is available upon request to Chief, U. S. Weather Bureau, Washington 25, D. C.

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MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: $3.00; additional for foreign mailing, $1.00; 30¢ per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

The printing of this publication has been approved by the Director of the Bureau of the Budget, February 9, 1955.

DEPARTMENT OF COMMERCE
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MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

Volume 83
Number 12

DECEMBER 1955

Closed February 15, 1956
Issued March 15, 1956

A SIMULTANEOUS LAGRANGIAN-EULERIAN TURBULENCE EXPERIMENT [1]

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[Manuscript received October 28, 1955; revised January 9, 1956]

ABSTRACT

Simultaneous measurements of turbulent vertical velocity fluctuations at a height of 300 ft. measured by means of a fixed anemometer, small floating balloons, and airplane gust equipment at Brookhaven are presented. The resulting Eulerian (fixed anemometer) turbulence energy spectra are similar to the Lagrangian (balloon) spectra but with a displacement toward higher frequencies.

1. THE NATURE OF THE PROBLEM

The term *Eulerian,* in turbulence study, implies consideration of velocity fluctuations at a point or points fixed in space, as measured for example by one or more fixed anemometers or wind vanes. The term *Lagrangian* implies study of the fluctuations of individual fluid parcels; these are very difficult to measure. In a sense, these two points of view of the turbulence phenomenon are closely related to the two most palpable physical manifestations of turbulence, first the irregular or *random* nature of the turbulent fluctuations and second the remarkable ability of fluid in a state of turbulence to disperse properties. Such problems of turbulence in the atmosphere as the effect of gusts on structures (towers, buildings, airframes) lead to the Eulerian kind of analysis, whereas the Lagrangian form arises naturally in the highly important field of atmospheric diffusion.

The irregular nature of turbulence early suggested, in fact imposed, a statistical rather than a deterministic approach to its study. Certain important quantities have emerged, with the development of this theory, that serve to characterize turbulence, chiefly the *energy spectrum function*, and the closely related *autocorrelation function*. This paper reports an attempt to make measurements of both Lagrangian and Eulerian turbulence fluctuations simultaneously. This problem owes its importance largely to the fact that experimenters usually measure the Eulerian-time form of the turbulence spectrum or correlation, which all fixed measuring devices of turbulence record; but theoretical developments as well as practical applications inevitably require the Eulerian-space, or the Lagrangian form. Consequently, both experimental verification of theoretical developments and the application of the theories to many practical problems require some consideration of the Eulerian and Lagrangian interrelationships.

2. OBSERVATIONAL TECHNIQUES

A comparatively wide variety of instruments is available for direct Eulerian-time observation of the natural wind at low elevations, the only requirement being that the device should respond to fluctuations in both the vertical and horizontal directions as rapidly as is required by the frequencies of fluctuations that are to be studied. Hot wire and thermopile anemometers [6], and bidirectional wind vanes of several types [6], [13], have all been used, as well as more unusual devices like the anemoclinometer [12], and tethered balloons [7]. Presumably any of these,

[1] This research was conducted under an agreement between the U. S. Weather Bureau and the U. S. Atomic Energy Commission.

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if available in quantities of at least two, could be used for Eulerian-space observations. Few such analyses have been reported; the observations of Shiotani [24], with hot wire anemometers arranged in the vertical, are one example. Sakagami has recently, in two fascinating papers [22], [23], reported on some spatial wind fluctuation measurements of very small-scale turbulence, obtained by using an array of tiny wind vanes, each only a centimeter long. Airplane gusts measurements, for example those reported by Bunker and McCasland [2] or Press and Mazelsky [20], provide a kind of Eulerian-space information. Although the sampling time of such measurements is finite, it is short enough that a relatively large space is sampled quite rapidly. Such measurements represent a fairly close approach to true Eulerian-space observations.

The method invariably employed in Lagrangian observations of atmospheric turbulence has been to introduce some tracer into the air and follow its motion. The list of tracers that have been employed (most of them were first tried by L. F. Richardson [21]) is, as Edinger [4] remarked, entertaining, including as it does Edinger's soap bubbles, Miller's Kleenex lint experiments [15], and the work done by Badgley [1] using dandelion seed. Balloons of various sizes have of course been used, also; and some work has been done by following smoke puffs, using a camera obscura [3]. The difficulty is to find a tracer that has negligible mass, zero terminal velocity or net buoyancy, is small enough to represent, faithfully, the smallest significant scale of air motions, and that can be traced by some reasonably convenient system. Certain of the above tracers satisfy one or more of these criteria, but no one satisfies all.

Considering this great diversity of measuring systems, it is clear that some care must be exercised in intercomparing various results. Different devices possess entirely different response properties, and size alone introduces a strong selective effect upon the fluctuations that can be measured. Bunker's PBY airplane is certainly indifferent to a range of small turbulent fluctuations that, say, Edinger's soap bubbles will detect easily. Considerations of this kind have been an important factor in the design of the following experiment.

3. A SIMULTANEOUS EULERIAN-TIME, EULERIAN-SPACE, AND LAGRANGIAN TURBULENCE EXPERIMENT

The Brookhaven National Laboratory, on eastern Long Island, maintains a permanent micrometeorological installation including a completely instrumented, 410-ft. high meteorological tower. A general description of this site has been given by Smith and Singer [25]. For wind fluctuation measurements, there are available at Brookhaven permanently mounted bidirectional wind vanes, or *bivanes*, at three levels on the tower, and Bendix-Friez *Aerovane* anemometers at these three as well as several other levels. The bivanes give the inclination of the wind, and the Aerovanes provide the wind speed and horizontal direction. Instrumental characteristics of the Brookhaven bivanes were described in a study by Mazzarella [13]; and the manner of their use in wind fluctuation measurement, in connection with the Aerovanes, is covered in several papers of Panofsky [17], [18], Panofsky and McCormick [19], and McCormick [11]. The technique may now be considered to be a tested, reliable one for obtaining low-level wind fluctuation data, possessing well understood properties and limitations.

It was accordingly proposed to make simultaneous observations of turbulent fluctuations in the lower atmosphere, with both the fixed bivane-Aerovane apparatus on the Brookhaven tower and visual double theodolite observations of neutral balloons, released from the tower. The cooperation of Mr. Andrew Bunker, Woods Hole Oceanographic Institution, was also obtained; his group agreed to attempt airplane measurements of vertical accelerations at the tower level during the same period. In this way, all three of the space, time, and Lagrangian fluctuations could be estimated at the same time.

Standard practice with the bivane data, because of the instrument's resonant period, is to work with 5- or 10-second averages of the velocity fluctuations, depending on the prevailing wind speed. Resulting spectra often show two peaks, or at least two more or less distinct high energy regions, one at a frequency of about 200 c. p. h., attributed to mechanical turbulence, and another at about 40 c. p. h., due presumably to convection. Since visual triangulation on small balloons any more often than every 10 seconds seemed an impossible prospect, it was thought best to choose a period for the experiment when the convective turbulence would be reasonably well developed. Based on the climatological expectancy of clear days, the period June 14 to 18, 1954, was chosen. This choice was also influenced by the requirement that all three of the different systems for measuring turbulence should provide comparable information. All three systems have a limited ability to respond to high-frequency fluctuations, and so it was thought best to concentrate on the lower, convective frequencies.

4. OBSERVATIONAL TECHNIQUE OF NEUTRAL BALLOONS

Bivane-Aerovane turbulence observations are a standard technique at Brookhaven and have been described in several papers referred to previously. The airplane gust measuring system used by Bunker is described in [2]. The technique of making neutral balloon runs, although familiar, was modified sufficiently in the present experiment to deserve some additional comment.

The basic double theodolite procedure is described in a Weather Bureau Circular [28], and by Lange [10] or Mildner, Hänsch, and Griessbach [14], for example. A number of standard precautions concerning orientation of

the baseline, collimation of the theodolites, and so on, are customarily advocated; all these were taken. The instruments used were standard, Gurley-type theodolites, on which the fractional portion of the angular readings appears on the knobs of the tangent screws. The baseline was 1250 ft. long, one station being on top of the Brookhaven meteorological building and the other in an adjacent open field.

Since angular readings each 10 seconds were desired, in order to obtain as detailed a record of the turbulent fluctuations as possible, each theodolite was manned by three people, an observer and two reader-recorders. Timing was provided from a central point, by radio and telephone, to the two stations. The exact manner of making the angular readings is believed to have been quite important in the success that was obtained. The theodolite observer's duty was to keep the instrument's cross hairs centered on the balloon at all times, with no pauses during readings. The two readers, one for azimuths and one for elevation angles, made their readings in the following order: tenths, then hundredths (estimated), and finally whole degrees. This procedure permitted readings to be synchronized closely with the time signals and is strongly recommended to future users of the technique.

Balloons were released from the 300-ft. level of the tower. They were inflated to a nearly neutral condition with the help of a wire hoop of predetermined size, and were fastened to the tower in an exposed position for several minutes. This preliminary exposure was done in a position sheltered from the wind, as much as possible, but exposed to the sun's rays, in order to approximate as nearly as could be done the conditions experienced during balloon flight.

Final weighing off was done by a method suggested to the writer by Mr. Paul Humphrey (U. S. Weather Bureau), and one that also is strongly indorsed in the light of our experience. A length of twine tied to the balloon's neck was allowed to rest on a shelf (inside the elevator cage of the tower, so as to be sheltered from the wind). When the balloon came to rest, the twine was cut where it touched the shelf. This process took less than 30 seconds, usually; and it could be repeated if necessary up to within a few seconds of the release of the balloon. Excess twine was merely wrapped around the balloon's neck and tied. Since this weighing off was to within a precision of two or three inches of string, which weighed .05 gm./in., the balloons were estimated to possess at most ±.2 gm. free lift on release.

5. SIMULTANEOUS BIVANE-AEROVANE, NEUTRAL BALLOON, AND AIRPLANE TURBULENCE MEASUREMENTS AT BROOKHAVEN

During the week of operations at Brookhaven, 35 neutral flights were made. Of these, 16 lasted less than 5 minutes and 3 longer than 20 minutes. The skill of the observers naturally increased as more experience was gained, the longer flights being achieved only after several days' practice. For this and various other reasons, mainly having to do with occurrence of optimum meteorological conditions and with the orientation of the wind with respect to the tower, the 6 flights made on the final day, June 18, were selected for study.

Corresponding to each of these 6 runs there is a so-called bivane "speed run", i. e., a bivane-Aerovane observation at accelerated chart speed, providing detailed vertical and horizontal velocity recordings. The wind instruments mounted at the 300-ft. level of the tower, from which level the neutral balloons were released, have been used for comparison with the neutral observations.

The airplane gust measurements, being at the mercy of weather conditions all the way from Woods Hole to Brookhaven, resulted during this period in only one clear-cut run that corresponded to a successful neutral flight, the very last one, number 35.

REDUCTION OF THE NEUTRAL BALLOON OBSERVATIONS

For maximum detail velocities were calculated from the neutral runs on a non-overlapping basis; that is, each 10-second interval was considered separately, the positions of the balloon being interpreted as due to a 10-second averaged velocity fluctuation. Otherwise, the standard method for working up double theodolite runs was used (cf [28]). Some effects of this on the resulting spectra will be considered in the following section.

The inspection of the balloon observations that takes place during the reduction process was used to detect one possible source of observational error in the readings. It is quite easy, when attempting the difficult job of reading theodolite azimuth and elevation angles every 10 seconds, to make an error of 1 in the units figure (a gross error of 10° or 100° is, of course, immediately detected). Such a unit error is, however, fairly easy to detect, inasmuch as all the angular readings should form relatively smooth progressions. It is indicative of the high quality of these observations that only two errors of this kind were found.

COMPUTED VERTICAL VELOCITY ENERGY SPECTRA

Both the bivane-Aerovane and neutral balloon observations indicate all three components of the velocity fluctuations, whereas the airplane gust measurements give the vertical fluctuations only. Also, the mean vertical velocity may for our purpose always be assumed to be zero; the mean horizontal velocity in the atmosphere is, on the other hand, a conception that has been questioned by several workers in the turbulence field. Largely for these reasons, only the spectra of vertical velocity fluctuations have been considered in this study.

In trying to analyze such a complicated and irregular pattern as a turbulent flow, one is quite naturally lead to represent it as the sum of many harmonic components of various frequencies, each possessing some share of the total turbulent kinetic energy. We think of the energy spectrum of turbulence as the distribution of this energy

over all the various frequencies. In order to obtain the energy spectrum, a harmonic analysis of the turbulent flow might in fact be attempted; but this approach would in practice usually turn out to be very difficult. We may obtain a fully equivalent result by first forming the autocorrelation function and then performing on it the Fourier analysis. In short, knowledge of the correlation is equivalent to knowledge of the spectrum and vice versa.

The technique of the numerical analysis of the observed vertical velocity fluctuations is that developed by the Atmospheric Turbulence Project at The Pennsylvania State University; it has been outlined briefly in the papers of Panofsky [17], [18] and described in all relevant detail by Van der Hoven [29]. This technique involves, essentially, forming the lagged products of the observed series of velocity components (autocorrelation) and performing a harmonic analysis on these (Fourier transformation). The resulting values, one corresponding to each of the lags, are known as spectral estimates of the energy density at the various frequencies. Following suggestions of Tukey [26], [27] various secondary operations are also performed: the original velocity series is first of all "pre-whitened." Pre-whitening involves first a certain transformation of the original data (see eq. (5), Appendix); and then at an appropriate point the spectrum of the pre-whitened variable is transformed back to the true spectrum (see eq. (13), Appendix). At a strategic point in the numerical process an averaging is done, to compensate for the finite length of the observational record; and finally the effect of the averaged nature of the original velocity values is taken into account.

There are a moderate number of alternatives to the above numerical process for spectral analysis, including the use of electronic, mechanical, or graphical harmonic analyzers. The numerical method has certain advantages, principally that it is always directly reproducible and does not itself introduce any new uncertainty or subjectivity. Furthermore, the sampling theory for spectral estimates obtained in this way has been worked out by Tukey [27], so that it is possible to form some notion of their reliability.

The chief disadvantage of the numerical method of spectral analysis is the fact that for detailed analysis of the lower frequencies many lags are needed, and the numerical work becomes prohibitive for desk calculators. Instead, the 10-second averages may themselves be averaged, into 20- and 40-second averages, and so on; analysis of these averaged series will, for a given number of lags (that is, a given amount of hand calculation) provide spectral estimates of correspondingly lower frequencies. It has been shown (see, for example, Van der Hoven's dissertation [29]) that, by neglecting in each case the 20 to 30 percent of the spectral estimates of highest frequency, a series of spectra corresponding to increasing averaging periods of one set of velocity observations may be combined to form a composite spectrum, giving the required detail in the low frequencies.

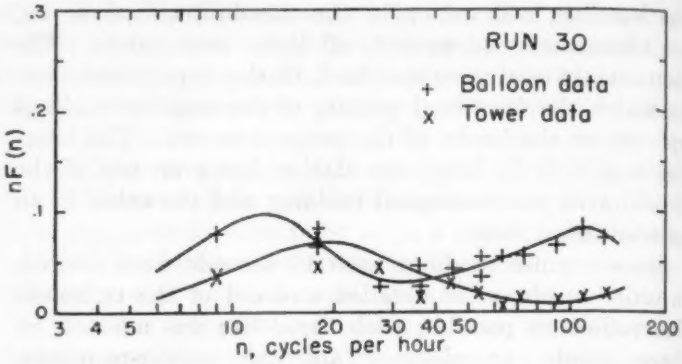

FIGURE 1.—Computed vertical velocity energy spectra for tower and neutral balloon runs number 30.

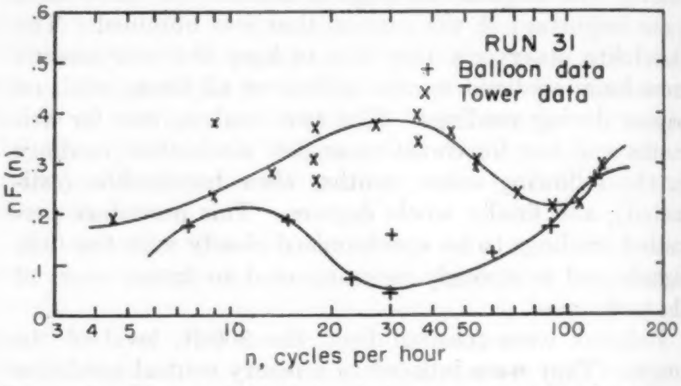

FIGURE 2.—Computed vertical velocity energy spectra for tower and neutral balloon runs number 31.

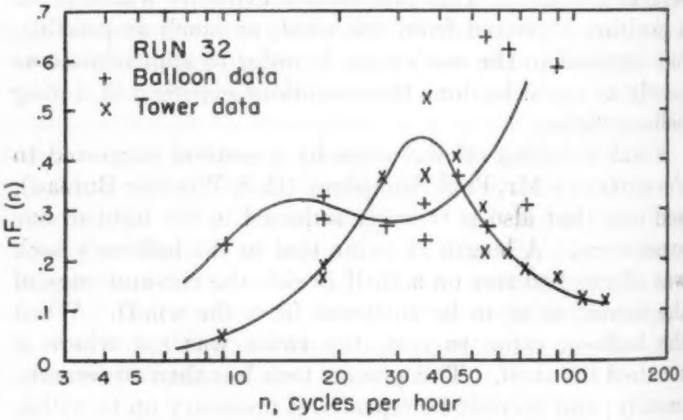

FIGURE 3.—Computed vertical velocity energy spectra for tower and neutral balloon runs number 32.

6. RESULTS

Figures 1 through 6 display the calculated vertical velocity spectra for both bivane speed runs and neutral balloon flights numbers 30 through 35, calculated by the numerical technique. Individual spectral estimates are indicated and suggested continuous spectral curves drawn. Figure 7 is the spectral analysis of Bunker's airplane run number 772, made during the progress of our run number 35. In order to portray the lower frequencies adequately, the logarithm of frequency is used as abscissa

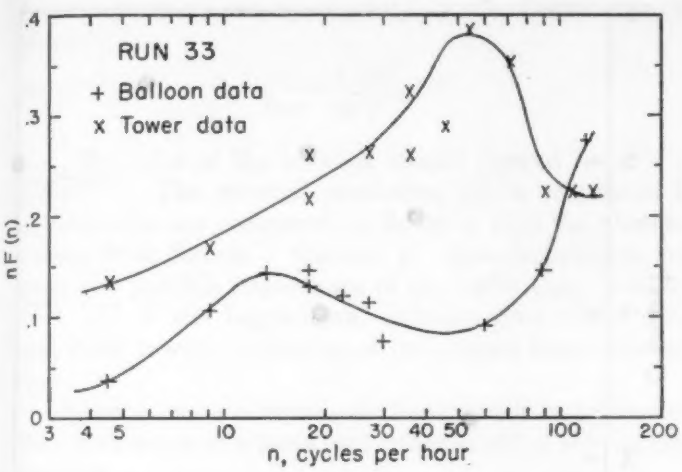

FIGURE 4.—Computed vertical velocity energy spectra for tower and neutral balloon runs number 33.

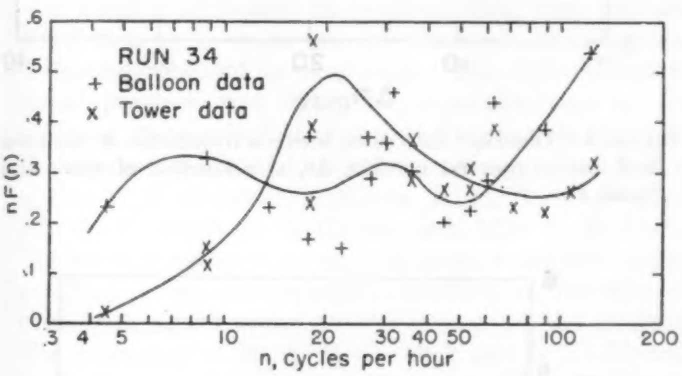

FIGURE 5.—Computed vertical velocity energy spectra for tower and neutral balloon runs number 34.

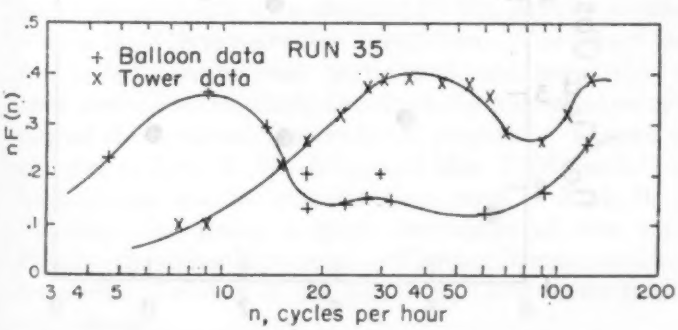

FIGURE 6.—Computed vertical velocity energy spectra for tower and neutral balloon runs number 35.

in these plots. The spectral energy estimate at each frequency is accordingly multiplied by frequency ([29] may be consulted for a discussion on this point).

These results are the first direct, simultaneous measures of Eulerian and Lagrangian turbulent fluctuations in the atmosphere to be reported. Although limited as to frequency range and imperfect in many respects, they are certain to be of considerable interest to students of the turbulence problem. The results are quite satisfying in a qualitative sense. The general picture that is conveyed

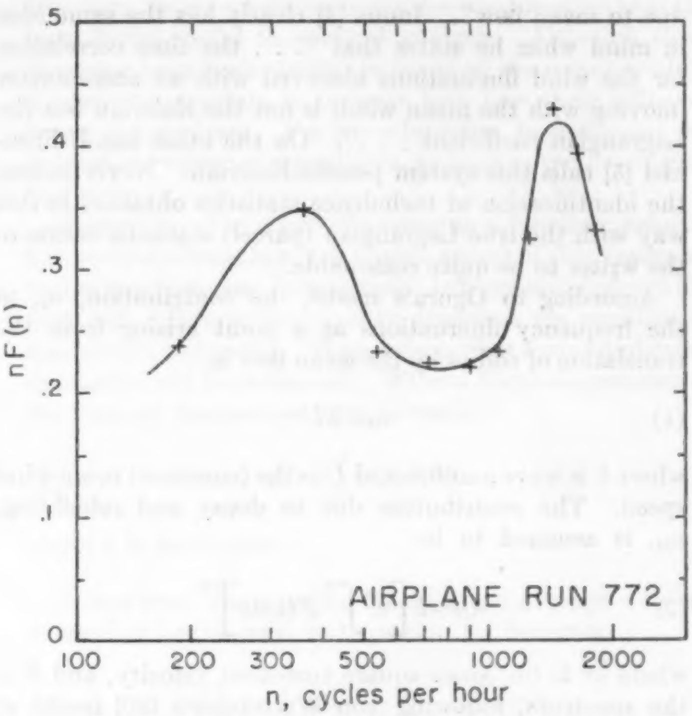

FIGURE 7.—Computed vertical velocity energy spectrum for PBY airplane run number 772.

by a comparison of the six pairs of tower (Eulerian) and neutral balloon (Lagrangian) spectra, figures 1 through 6, is that the Lagrangian spectra are generally similar in shape to the Eulerian spectra but displaced from them toward lower frequencies. If one forms only a very crude mental picture of the turbulence, say that it consists of a series of alternately positive and negative fluctuations, it might be conceived to be acting at a point that is moving along with the mean flow in this way (using an obvious symbolism):

$$+++++-----++++-+++++++++--.$$

If such a pattern is translated past a point with some speed, an observer at this point might perceive something like this:

$$+-+-+-+-+-+-+-+-+-.$$

In other words, the effect of translation past a point by the mean wind of some turbulent pattern is, qualitatively, to shift the significant fluctuations toward higher frequencies, with respect to observations made at a point. This is just what is observed, according to figures 1 through 6.

A quantitative comparison of the Lagrangian and Eulerian time spectra is afforded by Ogura's model of isotropic turbulence [16]. Ogura supposes that "the time variation of the wind velocities at a fixed point is caused both by the passage of the turbulent element and by the decay and rebuilding process of that element without any translation

due to mean flow". Inoue [8] clearly has the same idea in mind when he states that ". . . the time correlation for the wind fluctuations observed with an anemometer [moving with the mean wind] is not the Eulerian but the Lagrangian coefficient . . .". On the other hand, Frenkiel [5] calls this system psuedo-Eulerian. Nevertheless, the identification of turbulence statistics obtained in this way with the true Lagrangian (parcel) statistics seems to the writer to be quite reasonable.

According to Ogura's model, the contribution, n_I, to the frequency fluctuations at a point arising from the translation of eddies by the mean flow is

$$n_I = kU \tag{1}$$

where k is wave number and U is the (constant) mean wind speed. The contribution due to decay and rebuilding, n_{II}, is assumed to be

$$n_{II} = k\left[\overline{w^2}\int_k^\infty F(k)dk\right]^{1/2} \tag{2}$$

where $\overline{w^2}$ is the mean square turbulent velocity, and F is the spectrum, following von Weizsäcker's [30] model of turbulence. The total frequency fluctuation at a point, n, is then

$$n = n_I + n_{II} \tag{3}$$

If the Lagrangian contribution is identified with n_{II}, and if the spectral maxima are chosen for the sake of comparison, then the difference in maximum frequency between the Eulerian-time and Lagrangian spectra is given by $n - n_{II}$. Thus the difference between the tower and balloon spectral maxima, Δn, should be proportional to the mean wind. Figure 8 shows this comparison for runs 30 through 35, and a linear relation is certainly indicated. The factor of proportionality should equal the wave number of the spectral maximum. If one assumes that Bunker's airplane run (fig. 7) is equivalent to the Eulerian-space data, then the observed spectral maximum is at .00175 cycles per meter. This corresponds to an airspeed of 57 meters per second. The wave number computed from

$$n - n_{II} \equiv \Delta n = kU$$

where for run 35 the mean wind is 5.5 meters per second and Δn equals 31 cycles per hour, turns out to be .00156 cycles per meter, in good agreement with the actual value.

If Ogura's suggested interpolation formula for the wave number spectrum,

$$F\left(\frac{k}{k_0}\right) = \frac{2}{3}\frac{k/k_0}{\{1+(k/k_0)^2\}^{4/3}} \tag{4}$$

is introduced into equation (2), it follows after integration that

$$n_{II} = \sqrt{\overline{w^2}}\cdot\frac{k}{\{1+(k/k_0)^2\}^{1/6}} \tag{5}$$

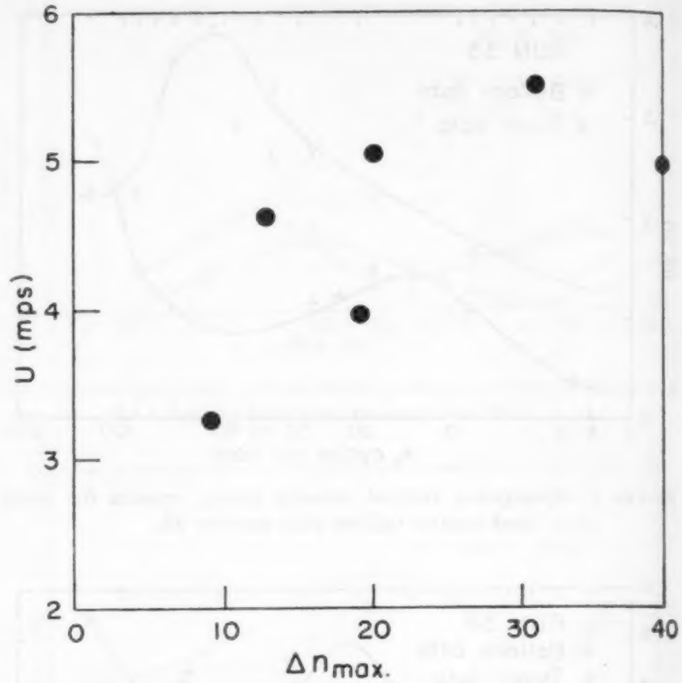

FIGURE 8.—Observed differences between frequencies of the tower and balloon spectral maxima, Δn, as a function of mean wind speed, U.

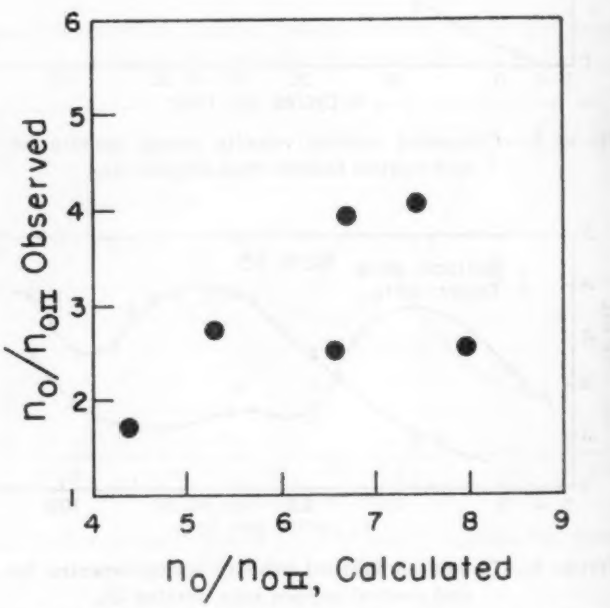

FIGURE 9.—Observed and calculated ratios of the tower and balloon spectral maximum frequencies.

where k_0 is an arbitrary reference wave number, for convenience chosen to be the spectral maximum. Consequently,

$$n_{0II} = \frac{k_0\sqrt{\overline{w^2}}}{(2)^{1/6}}$$

If we again identify this with the Lagrangian contribution, and form the *ratio* of the Eulerian-time spectral

frequency maximum, $n_0=n_{0I}+n_{0II}$, to the Lagrangian, we obtain

$$\frac{n_0}{n_{0II}}=\frac{1.12U}{(\overline{w^2})^{1/2}}+1 \tag{6}$$

i. e., the ratio of the maxima should depend linearly on $U/(\overline{w^2})^{1/2}$. The spectral maximum ratios calculated by equation (6) are compared, in figure 9, with the observed values from figures 1 through 6. The comparison suggests the possible importance of the turbulence intensity, $(\overline{w^2})^{1/2}/U$, in the Lagrangian, Eulerian-time relationship, and there is some indication of the desired linear relationship.

Although these comparisons leave much to be desired, they may serve as a basis for further study of this difficult problem.

ACKNOWLEDGMENTS

A number of people have given their time and skill freely in order to make this work possible, and the writer is sincerely grateful for their help. The difficult observational program was the joint accomplishment of four separate meteorological groups. Participants from the Brookhaven National Laboratory meteorological staff included M. E. Smith, I. A. Singer, R. M. Brown, F. Bartlett, G. W. Potts, G. S. Raynor, and Miss C. M. Smith. Their ready cooperation, as well as the availability of the excellent micrometeorological facilities at Brookhaven, were both fundamental to the success of the program. The assistance of R. A. McCormick and G. DeMarrais, U. S. Weather Bureau, and D. L. Jones and I. Van der Hoven, Department of Meteorology, The Pennsylvania State University, was likewise invaluable. The airplane gust measurements were obtained by Mr. Andrew Bunker, Woods Hole Oceanographic Institution. The writer feels deeply indebted to each participant, and hopes that all have derived some satisfaction from the successful completion of this unusual observational program. Thanks are also due to Mrs. R. Spaulding and Mrs. V. Mares for performing the spectral computations, and to Prof. H. A. Panofsky for many helpful discussions of the work. Finally, the writer is grateful to Weather Bureau reviewers for a critical review of the manuscript and many helpful suggestions.

APPENDIX

EFFECTS OF AVERAGING AND PRE-WHITENING ON CALCULATED SPECTRA

Any series of turbulent wind velocity fluctuations must necessarily undergo several modifications before appearing as an analyzed spectrum. Observations of velocity fluctuations have usually been subjected to two modifications prior to, or after, Fourier analysis. *Averaging* of the velocity fluctuations in the case of the bivane observations is necessary because of the bivane's resonant period. The neutral balloon observations of wind velocities are also averages, because of the interval between successive readings. The process known, in Tukey's picturesque terminology, as *pre-whitening* is another modification that has been found useful in spectral analysis. Although these processes have been applied in many of the recent studies, it seems appropriate to indicate here how their influence enters the analysis. For pre-whitening, in particular, no discussion seems to be available, at least in meteorological literature.

Averaging.—The effect of averaging a function, prior to harmonic analysis, is a well known aspect of this venerable tool of research; see, for example, Jeffreys and Jeffreys [9], page 450. Ogura has recently discussed the problem in energy spectral terms. Here a somewhat less complicated derivation will be presented. When a Fourier expansion of the velocity fluctuation, $u(t)$, is made,

$$u(t)=\int \phi(n)e^{int}dn \tag{1}$$

where n is frequency.

If, however, the velocity record is an average over an interval of length, say, $2a$, equation (1) becomes

$$\overline{[u(t)]}_{2a}=\int \phi(n)\cdot\frac{1}{2a}\int_{t-a}^{t+a} e^{in\tau}d\tau dn. \tag{2}$$

By a straightforward integration, we obtain

$$\overline{[u(t)]}_{2a}=\int \phi(n)\frac{\sin (na)}{na}e^{int}dn. \tag{3}$$

Here the true amplitudes, $\phi(n)$, are suppressed by a factor $(\sin na)/na$. Squaring the amplitude to obtain the spectrum, it is found that the observed and true spectra are related by

$$F_{true}(n)=\frac{(na)^2}{\sin^2 (na)}F_{avg}(n). \tag{4}$$

Pre-whitening.—In general, the numerical process for the spectral analysis of the velocity fluctuations does not work well where the spectrum varies rapidly as a function of frequency; in fact, spectra computed by Tukey's method sometimes show negative energy at high frequencies. To get around this difficulty, Tukey suggested the following: if u_j represents the original set of averaged velocity values, then define a new set of values such that

$$y_j=u_j-bu_{j-1} \tag{5}$$

where b is some constant, $0<b<1$. In practice one would first have removed the mean velocity, i. e.,

$$y_i=(u_j-\overline{u_j})-b(u_{j-1}-\overline{u_{j-1}})$$

but for simplicity of notation let us consider (5). This has the effect of suppressing long-period fluctuations relative to short-period fluctuations.

Forming the lagged products,

$$y_jy_{j+m}=(u_j-bu_{j-1})\ (u_{j+m}-bu_{j+m-1}) \tag{6}$$

and expanding and collecting terms, one obtains

(7) $y_j y_{j+m} = u_j u_{j+m} - b u_{j-1} u_{j+m} - b u_j u_{j+m-1} + b^2 u_{j-1} u_{j+m-1}$

In functional notation for continuous t, this is equivalent to

(8) $$y(t)y(t+m\tau) = u(t)u(t+m\tau) - bu(t-\tau)u(t+m\tau) - bu(t)u(t+m\tau-\tau) + b^2 u(t-\tau)u(t+m\tau-\tau)$$

where τ is the time interval between the original set of values u_j. Putting $h \equiv m\tau$, the ordinary autocorrelation $R(h)$ is formed by summing and averaging terms such as the first one on the right; the terms with coefficients $-b$, however, define slightly different correlations, $R(h+\tau)$ and $R(h-\tau)$. Summing and averaging the terms in (8) therefore gives

(9) $$R_{pre}(h) = (1+b^2)\,R(h) - bR(h+\tau) - bR(h-\tau)$$

where $R_{pre}(h)$ is the autocorrelation for the pre-whitened variable. The Fourier transform of (9) is obtained by multiplying through by $\frac{1}{2\pi} e^{inh}\,dh$ and integrating. This gives

(10) $$F_{pre}(n) = (1+b^2)F(n) - \frac{b}{2\pi}\int e^{inh}R(h+\tau)dh - \frac{b}{2\pi}\int e^{inh}R(h-\tau)dh.$$

But (10) is equivalent to

(11) $$F_{pre}(n) = (1+b^2)F(n) - \frac{be^{-in\tau}}{2\pi}\int e^{in(h+\tau)}R(h+\tau)d(h+\tau) - \frac{be^{in\tau}}{2\pi}\int e^{in(h-\tau)}R(h-\tau)d(h-\tau)$$

which gives

(12) $$F_{pre}(n) = (1+b^2)F(n) - be^{-in\tau}F(n) - be^{in\tau}\,F(n).$$

Since $\cos n\tau = \frac{e^{in\tau}+e^{-in\tau}}{2}$, equation (12) reduces to

(13) $$F_{pre}(n) = (1+b^2-2\,b\cos n\tau)F(n).$$

which shows the relation between the spectrum of the pre-whitened variable, $F_{pre}(n)$, and that of the original, $F(n)$.

This process can clearly be generalized so as to smooth out any unwanted spectral peaks. The true spectrum, $F(n)$, is then obtained, in its original "color", by the use of (13).

REFERENCES

1. F. I. Badgley, "Photographic Study of Turbulence." Occasional Report No. 2, *Atmospheric Turbulence Study*, Dept. of Meteorology and Climatology, University of Washington, 1952, 47 pp.
2. A. F. Bunker and K. McCasland, "Description and Installation of Meteorological Equipment Aboard Navy PBY-6A, 46683," Woods Hole Oceanographic Institution, *Report* 54-82, 1954.
3. C. S. Durst, "The Fine Structure of Wind in the Free Air," *Quarterly Journal of the Royal Meteorological Society*, vol. 74, Nos. 321/322, July/Oct. 1948, pp. 349-360.
4. J. G. Edinger, "A Technique for Measuring the Detailed Structure of Atmospheric Flow," U. S. Air Force, Cambridge Research Center, *Geophysical Research Papers* No. 19, 1952, pp. 241-261.
5. F. Frenkiel, "On the Kinematics of Turbulence," *Journal of the Aeronautical Sciences*, vol. 15, No. 1, Jan. 1948, pp. 57-64.
6. G. C. Gill, "Micrometeorological Instrumentation at MIT's Round Hill Field Station," U. S. Air Force, Cambridge Research Center, *Geophysical Research Papers* No. 19, 1952, pp. 171-185.
7. E. W. Hewson, *Research on Turbulence and Diffusion of Particulate Matter in the Lower Layers of the Atmosphere*, Final report, contract AF 28 (099)-7, Round Hill Field Station, Massachusetts Institute of Technology, 1951, 80 pp.
8. E. Inoue, "Interrelations Between the Structure of Wind Near the Ground and Its Observation," *Journal of the Meteorological Society of Japan*, vol. 30, No. 8, Aug. 1952, pp. 255-264.
9. H. Jeffreys and B. S. Jeffreys, *Methods of Mathematical Physics*, Cambridge (Gt. Brit.) University Press, 1950, 708 pp.
10. K. O. Lange, "Über Windströmungen an Hügelhindernissen," *Veröffentliche des Forschungsinstitut der Rhön—Rossiten Gesellschaft e. V.*, No. 4, 1929, pp. 1-29.
11. R. McCormick, "The Partition and Intensity of Eddy-Energy at the 91-metre Level during Unstable Conditions as Observed at Brookhaven National Laboratory," *Quarterly Journal of the Royal Meteorological Society*, vol. 80, No. 345, July 1954, pp. 359-368.
12. A. Martinot-Lagarde, A. Fauquet, and F. N. Frenkiel, "The IMFL Anemoclinometer—An Instrument for the Investigation of Atmospheric Turbulence," U. S. Air Force, Cambridge Research Center, *Geophysical Research Papers* No. 19, 1952, pp. 207-216.
13. D. A. Mazzarella, "An All-Weather, Remote-Recording Bivane," *Bulletin of the American Meteorological Society*, vol. 33, No. 2, Feb. 1952, pp. 60-66.
14. P. Mildner, F. Hänsch, and K. Griessbach, "Doppelvisierungen von Pilotballonen zur Untersuchung von Turbulenz und Vertikolbewegungen in der Atmosphäre," *Beiträge zur Physik der Freien Atmosphäre*, vol. 17, 1931, pp. 181-219.
15. J. E. Miller, "A Photographic Technique for Analyzing Turbulent Motions of Air," U. S. Air Force, Cambridge Research Center, *Geophysical Research Papers* No. 19, 1952, pp. 293-303.
16. Y. Ogura, "The Relation between the Space- and Time-Correlation Functions in a Turbulent Flow,"

Journal of the Meteorological Society of Japan, Series 2, vol. 31, Nos. 11/12, Dec. 1953, pp. 355–369.

17. H. A. Panofsky, "The Cooperative Turbulence Study of August 30–31, 1951 at the Brookhaven National Laboratory," Dept. of Meteorology, The Pennsylvania State University, *Scientific Report* No. 1, 1952, 49 pp.
18. H. A. Panofsky, "The Variation of the Turbulence Spectrum with Height under Superadiabatic Conditions," *Quarterly Journal of the Royal Meteorological Society*, vol. 79, No. 339, Jan. 1953, pp. 150–153.
19. H. A. Panofsky and R. McCormick, "The Vertical Momentum Flux at Brookhaven at 109 Meters," U. S. Air Force, Cambridge Research Center, *Geophysical Research Papers* No. 19, 1952, pp. 219–229.
20. H. Press and B. Mazelsky, "A Study of the Application of Power-Spectral Methods of Generalized Harmonic Analysis to Gust Loads on Airplanes," National Advisory Committee for Aeronautics, *Technical Note* No. 2853, 1953, 48 pp.
21. L. F. Richardson, "Atmospheric Diffusion Shown on a Distance-Neighbour Graph," *Proceedings of the Royal Society of London*, Series A, vol. 110, No. 756, April 1, 1926, pp. 709–737.
22. J. Sakagami, "On the Structure of the Atmospheric Turbulence Near the Ground," Ochanomizu University, *Natural Science Report*, vol. 1, 1951, pp. 40–50.
23. J. Sakagami, "On the Structure of the Atmospheric Turbulence Near the Ground. II," Ochanomizu University, *Natural Science Report*, vol. 2, 1951, pp. 52–61.
24. M. Shiotani, "Turbulence in the Lowest Layers of the Atmosphere," Tohuku University, *Science Report, Series 5 Geophysics*, vol. 2, No. 3, Dec. 1950, pp. 157–201.
25. M. E. Smith and I. A. Singer, "Applicability and Key to Meteorological Punch Card Data, April 1950–March 1952," Brookhaven National Laboratory, Upton, N. Y., Contract of AF 19 (604)–490, *Technical Report* No. 48, 1954, 12 pp.
26. J. W. Tukey, "Measuring Noise Color," Paper given at meeting of Institute of Radio Engineers, 7 November 1951.
27. J. W. Tukey, "The Sampling Theory of Power Spectrum Estimates," *Symposium on Application of Autocorrelation Analysis to Physical Problems*, U. S. Navy, Office of Naval Research, 1949.
28. U. S. Weather Bureau, "Manual of Winds-Aloft Observations," *Circular O*, July 1950.
29. I. Van der Hoven, Dissertation, Dept. of Meteorology, The Pennsylvania State University, 1955, (Unpublished).
30. C. F. Von Weizsäcker, "Das Spektrum der Turbulenz bei Grossen Reynoldsschen Zahlen," *Zeitschrift für Physik*, vol. 124, 1948, pp. 614–627.

AN EMPIRICAL INDEX OF SEASONAL VARIATION OF INTENSE PRECIPITATION OVER LARGE AREAS

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[Manuscript received May 16, 1955; revised November 10, 1955]

ABSTRACT

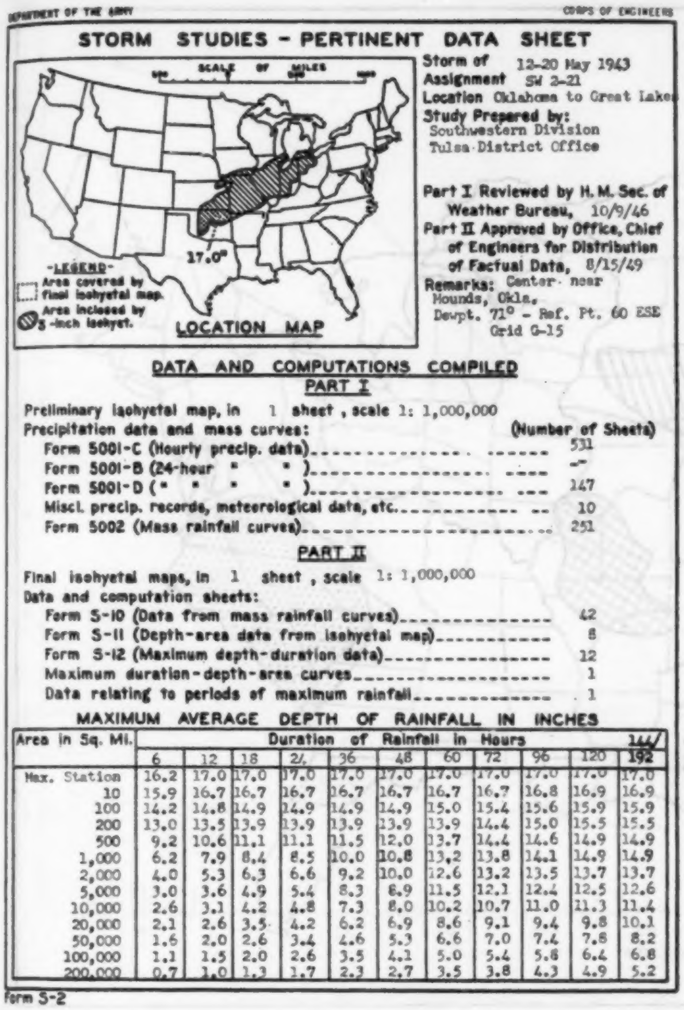
Adequate design and sound operational procedures for levees, spillways, and multiple-purpose reservoirs require a knowledge of seasonal variation of precipitation of high intensity as well as soil infiltration capacities, antecedent rainfall, and snow melt. The problem of seasonal variation is approached by indirect methods since there is an inadequacy of data on large storms. A technique of areal smoothing is introduced and used to overcome lack of suitable areal distribution of large storms studied in detail. A set of bi-weekly charts is developed giving approximately equal likelihood of occurrence of high rates of rainfall over areas of 20,000 square miles in 72 hours.

1. INTRODUCTION

The role of the hydrometeorologist in engineering design is to provide the engineer with as much meteorological information as possible which may contribute to safe and economical construction of a particular structure. In the design of levees, spillways, or multiple-purpose reservoirs the meteorological problem is not alone one of amounts of precipitation but, because of varying infiltration capacities of the soil, antecedent rainfall, snow melt, and other variables, it is also a problem of seasonal variations of precipitation of great intensity. To date the storm study program of the Corps of Engineers, Department of the Army [1] has encompassed about 600 storms of intense precipitation. This program is designed to study the depth-duration-area characteristics of major storms in the United States. Results are tabulated and published as pertinent data sheets as illustrated by figure 1. As yet, too few fall, winter, and spring storms have been studied to provide a suitable approximation to the true seasonal characteristics of large-area precipitation. Until such time that the meteorologist can set down a theoretical solution to the problem of precipitation, its causes and its seasonal characteristics, or until such time that an adequate portrayal of precipitation distributions can be presented by synoptic climatological means, approximations of the desired information will have to be made by engineering techniques. This paper presents one such engineering technique that serves as a partial solution to the problem of seasonal variation of intense precipitation over large areas.

J. B. Kincer [2] plotted the monthly State averages of precipitation for the 55-year period 1886–1940 and tabulated by States the percentages of years having averages of 0–.99, 1.00–1.99, 2.00–2.99, 3.00–3.99, 4.00–4.99, and 5.00+ inches. In the interest of utility, S. S. Visher [3] plotted some of the categories tabulated by Kincer and ventured to draw isolines on the charts to make the data easier to grasp. Under the direction of W. F. McDonald an activity of the Works Projects Administration reviewed and tabulated daily precipitation records from all stations operated by the Weather Bureau (see fig. 2) during the 30-year period, 1906–1935. These 24-hour amounts were summarized within standard weekly intervals beginning on January 1. The 29th of February once every four years and the last day of each year were included in the encompassing week, but the values for such periods were proportionally adjusted to a 7-day basis. Individual station weekly averages were plotted on charts and smoothed, as were average daily intensities. These charts are in published form [4] and are also printed on the back of *The Daily Weather Map* periodically. These data were also summarized and tabulated as weekly averages over each of the climatological divisions of the United States. Although most of the divisions are about 20,000 square miles in area their size varies considerably as can be seen in figure 3.

The Hydrometeorological Section of the Weather Bureau has from time to time studied portions of the seasonal variation of precipitation over particular drainage areas [5] and the seasonal variation of precipitation over small areas [6]. The data tabulated for climatological divisions serve as a basis for a generalized evaluation of the seasonal variation of precipitation over moderately large areas. It would be preferable to study seasonal variation of 72-hour rainfall directly. Since such data are not available the assumption is made that seasonal variation of weekly amounts and 72-hour amounts are reasonably consistent.



DEPARTMENT OF THE ARMY CORPS OF ENGINEERS

STORM STUDIES - PERTINENT DATA SHEET

SCALE OF MILES

17.0"

-LEGEND-
Area covered by final isohyetal map.
Area inclosed by 3-inch isohyet.

LOCATION MAP

Storm of 12-20 May 1943
Assignment SW 2-21
Location Oklahoma to Great Lakes
Study Prepared by: Southwestern Division Tulsa District Office

Part I Reviewed by H. M. Sec. of Weather Bureau, 10/9/46
Part II Approved by Office, Chief of Engineers for Distribution of Factual Data, 8/15/49
Remarks: Center near Mounds, Okla. Dewpt. 71° - Ref. Pt. 60 ESE Grid G-15

DATA AND COMPUTATIONS COMPILED

PART I

Preliminary isohyetal map, in 1 sheet, scale 1: 1,000,000
Precipitation data and mass curves: (Number of Sheets)
Form 5001-C (Hourly precip. data) 531
Form 5001-B (24-hour " ") .... --
Form 5001-D (" " " ") 147
Miscl. precip. records, meteorological data, etc. 10
Form 5002 (Mass rainfall curves) 251

PART II

Final isohyetal maps, in 1 sheet, scale 1: 1,000,000
Data and computation sheets:
Form S-10 (Data from mass rainfall curves) 42
Form S-11 (Depth-area data from isohyetal map) 8
Form S-12 (Maximum depth-duration data) 12
Maximum duration-depth-area curves 1
Data relating to periods of maximum rainfall 1

MAXIMUM AVERAGE DEPTH OF RAINFALL IN INCHES

Area in Sq. Mi.	Duration of Rainfall in Hours										
	6	12	18	24	36	48	60	72	96	120	144/192
Max. Station	16.2	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
10	15.9	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.8	16.9	16.9
100	14.2	14.8	14.9	14.9	14.9	14.9	15.0	15.4	15.6	15.9	15.9
200	13.0	13.5	13.9	13.9	13.9	13.9	13.9	14.4	15.0	15.5	15.5
500	9.2	10.6	11.1	11.1	11.5	12.0	13.7	14.4	14.6	14.9	14.9
1,000	6.2	7.9	8.4	8.5	10.0	10.8	13.2	13.8	14.1	14.9	14.9
2,000	4.0	5.3	6.3	6.6	9.2	10.0	12.6	13.2	13.5	13.7	13.7
5,000	3.0	3.6	4.9	5.4	8.3	8.9	11.5	12.1	12.4	12.5	12.6
10,000	2.6	3.1	4.2	4.8	7.3	8.0	10.2	10.7	11.0	11.3	11.4
20,000	2.1	2.6	3.5	4.2	6.2	6.9	8.6	9.1	9.4	9.8	10.1
50,000	1.6	2.0	2.6	3.4	4.6	5.3	6.6	7.0	7.4	7.8	8.2
100,000	1.1	1.5	2.0	2.6	3.5	4.1	5.0	5.4	5.8	6.4	6.8
200,000	0.7	1.0	1.3	1.7	2.3	2.7	3.5	3.8	4.3	4.9	5.2

Form S-2

FIGURE 1.—Example of data sheet for Corps of Engineers storm studies.

FIGURE 2.—Stations with 30-year precipitation records, 1906–1935, used in preparing weekly precipitation averages and 4-week charts of average daily precipitation intensity.

2. SEASONAL VARIATION OF INTENSE PRECIPITATION AS PERCENTAGE OF MAXIMUM

For each climatological division east of the Rockies all weekly averages greater than one inch were plotted at the appropriate week on a seasonal graph. It was felt that the sparsity of data, irregularities in size and shape of areas, and topographic influences precluded generalized studies of this sort for the western States. Figure 4 shows such a plot for western Tennessee, one of the 94 divisions studied. (The circled values are associated with storms already studied in the Corps of Engineers storm study program. Charts of this sort serve as good indicators of storms worthy of further study in the program.) On each such chart were drawn three curves; the highest curve representing an envelopment of observed weekly average rainfalls over the particular division, and the lowest representing the smoothed weekly averages obtained for the 30-year period. It will be noted that the smoothed weekly means indicate peaks of rainfall on the 13th and 14th weeks and again on the 52d week, whereas the enveloped values indicate a single peak on the 3d week. It is apparent from the plotted values that the double peak on the smoothed average curve results from a greater frequency of 2- and 3-inch amounts during that time of year—a significant fact in connection with water supply problems. However, from the viewpoint of spillway, flood reservoir, or levee design, the variations of the extreme or near extreme values are of primary interest.

Figure 5 shows the weekly precipitation over eastern Texas for the period 1906–1935, and again the highest curve represents envelopment of all observed values and the lowest curve represents the smoothed weekly means. The latter curve indicates two peak periods of rainfall—the 17th and the 49th and 50th weeks, again resulting from a predominance of weeks having 2- and 3-inch amounts of precipitation. In sharp contrast, the enveloping curve shows a marked peak at the 33d week with indications of secondary peaks on the 13th and 49th weeks. The peak on the enveloping curve is a result of weak tropical storms moving inland over the Texas area—infrequent for a particular area but not uncommon for the region adjacent to or just inland from the Gulf of Mexico. Such chance occurrences over a particular division tend to create an unstable curve of enveloped observed values which is highly dependent upon the combination of length of record and chance occurrences. From an engineering design viewpoint it is desirable to have a more stable curve upon which to base design estimates.

The middle curves in figures 4 and 5, labeled 99 percent, represent a seasonal distribution of intense rainstorms of unusual but not rare occurrence. Considerable judgment has gone into the drawing of these curves. Certain general rules can be enumerated as follows:

1. The data should serve as basic guides.

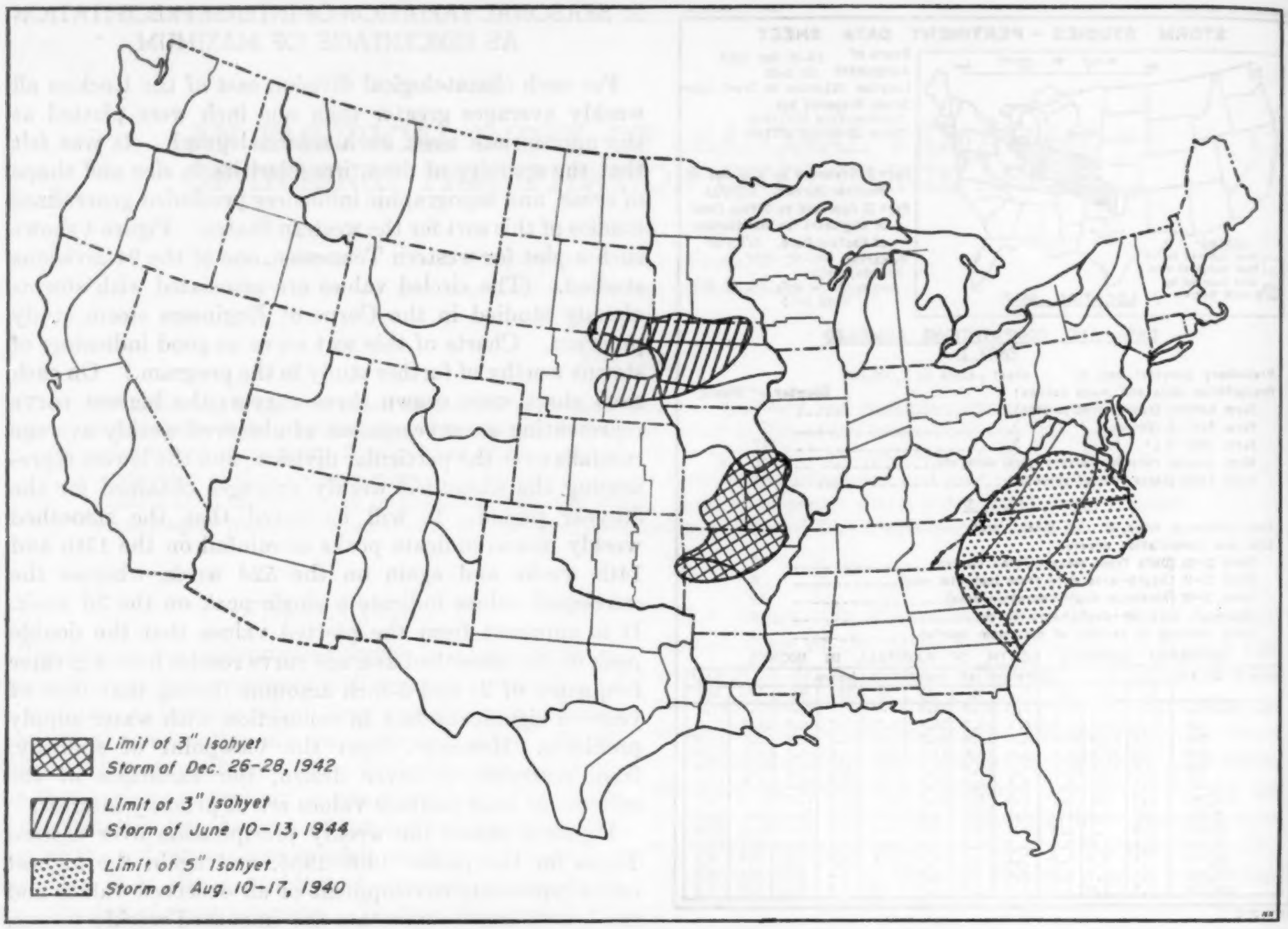


FIGURE 3.—Base map shows climatological divisions of the United States. Hatched areas show limits of heavy rain in three selected storm situations.

2. The curves should be fairly smooth, exhibiting no sharp discontinuities from one week to the next. The intent of this rule is not to deny the existence of singularities, but rather, to recognize the extreme difficulty in the proof of such singularities—a good number of which appeared to be indicated over the span of 30 years.

3. The number of points undercut on each seasonal graph should be approximately 15, 16 or 17 (approximately 1 percent of the total, 1,560 weeks). Some latitude had to be allowed in order to permit smoothing of curves to avoid sharp irregularities.

4. The points undercut should be fairly evenly distributed throughout the year.

5. The amount of undercutting of a particular point should be dependent upon the number of other high intensity values for that season and especially upon the clustering of points on or just below the tentative curve.

6. The curve for a particular division should be consistent with the curves of adjacent divisions with due consideration for topographic variation, geographic location with respect to moisture source, and variation in area of the climatological divisions.

The "99 percent curves" represent a first approximation to the seasonal variation of intense weekly precipitation over particular large areas. It is believed that a reasonable representation has been achieved in spite of the considerable degree of subjectivity required for the final lines. Furthermore, it is believed that, given the same basic data, another analyst following the general rules prescribed would obtain approximately the same curve. As an additional check upon the shape of the 99-percent curve, an additional curve was drawn undercutting approximately 78 points throughout the year (95 percent) whenever doubts arose concerning the shape of the 99-percent curve.

The size, shape, and orientation of storm isohyetal patterns as related to the topographic, geographic, and areal characteristics of the divisions play an important

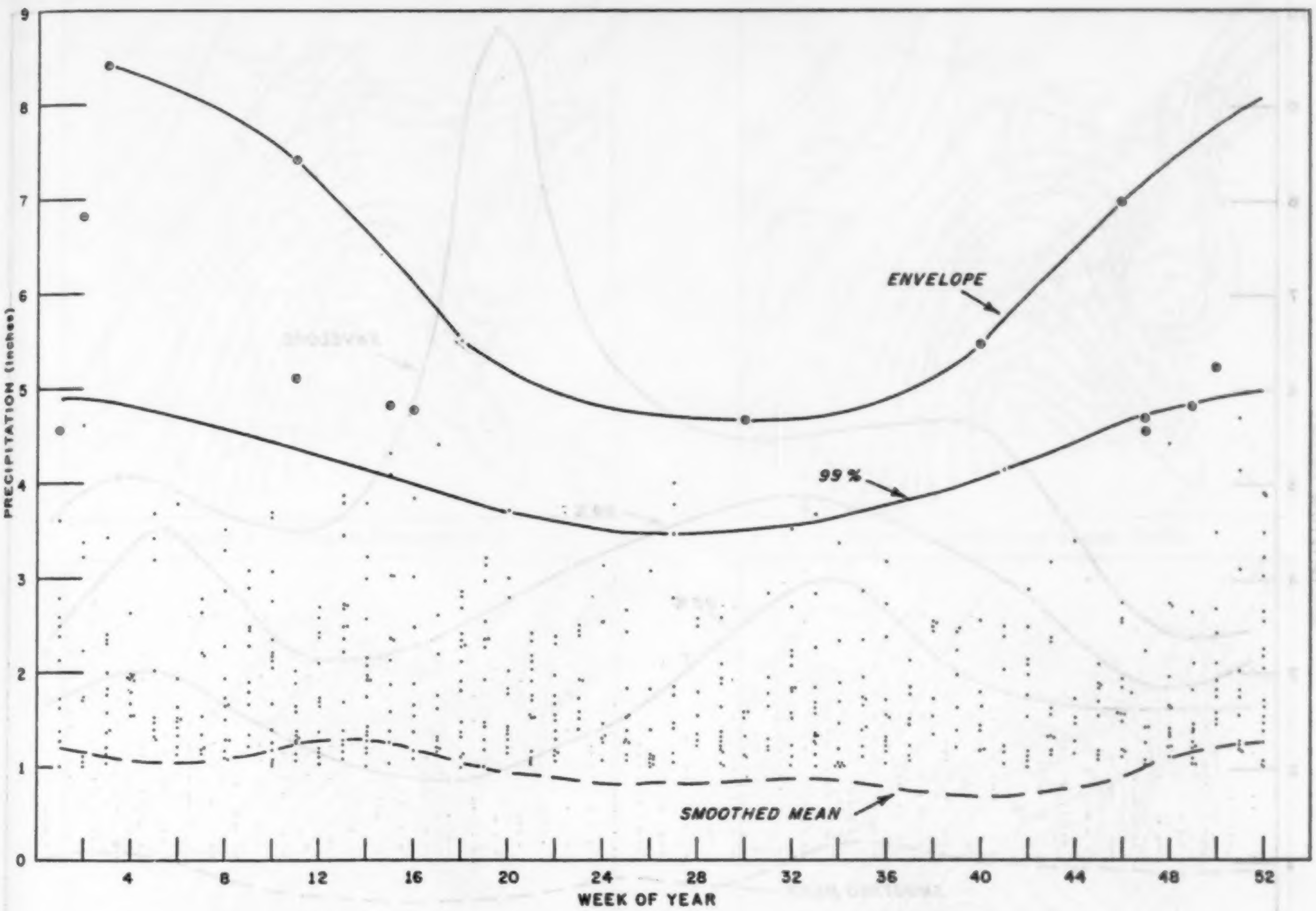


FIGURE 4.—Western Tennessee weekly precipitation greater than 1 inch, 1906–35. Circled dots are weekly totals greater than 4.5 inches, studied by Corps of Engineers.

role in the evaluation of seasonal variation. From figure 3, it is seen that a particular storm may be a good or poor match for selected areas of study such as States, climatological divisions, counties, or other arbitrarily bounded regions. Actually, the only completely adequate way of handling such a problem is to examine different orientations, shapes, and sizes separately as is done in the Corps of Engineers Storm Study Program. For hydrologic studiesindividual river basins are examined in detail as the problem arises. Because of the depth-area relationships, comparison of average amounts of precipitation in inches loses much of its meaning whether on a State, division, or county basis.

Therefore, a set of charts (dashed lines in figures 6–31) is presented as a generalized portrayal of seasonal variation of precipitation over large areas. These charts are the result of an additional step in smoothing which partly compensates for the differences in shape, size, and orientation. For each division, at bi-weekly intervals the ratio of the value of the 99 percent curve to the maximum value of the 99 percent curve of that division was computed. These values were plotted and smoothed percentage lines drawn. Considerable judgment was again applied in drawing these lines since the areal irregularities became more noticeable. Again certain general rules were adopted as follows:

1. In non-orographic areas smoothness of pattern was considered desirable. For example, a percentage value of 80 surrounded by 90's was considered a result of shape irregularity and was enveloped. The net effect of this procedure was to modify the basic 99 percent curve for the particular division by increasing its value at that particular time of year.

2. Major orographic features (Appalachians and slopes of Rockies) were allowed to play dominant roles and became boundaries of rather sharp discontinuities. Minor meteorological controls (Ozarks and Great Lakes) were given less consideration.

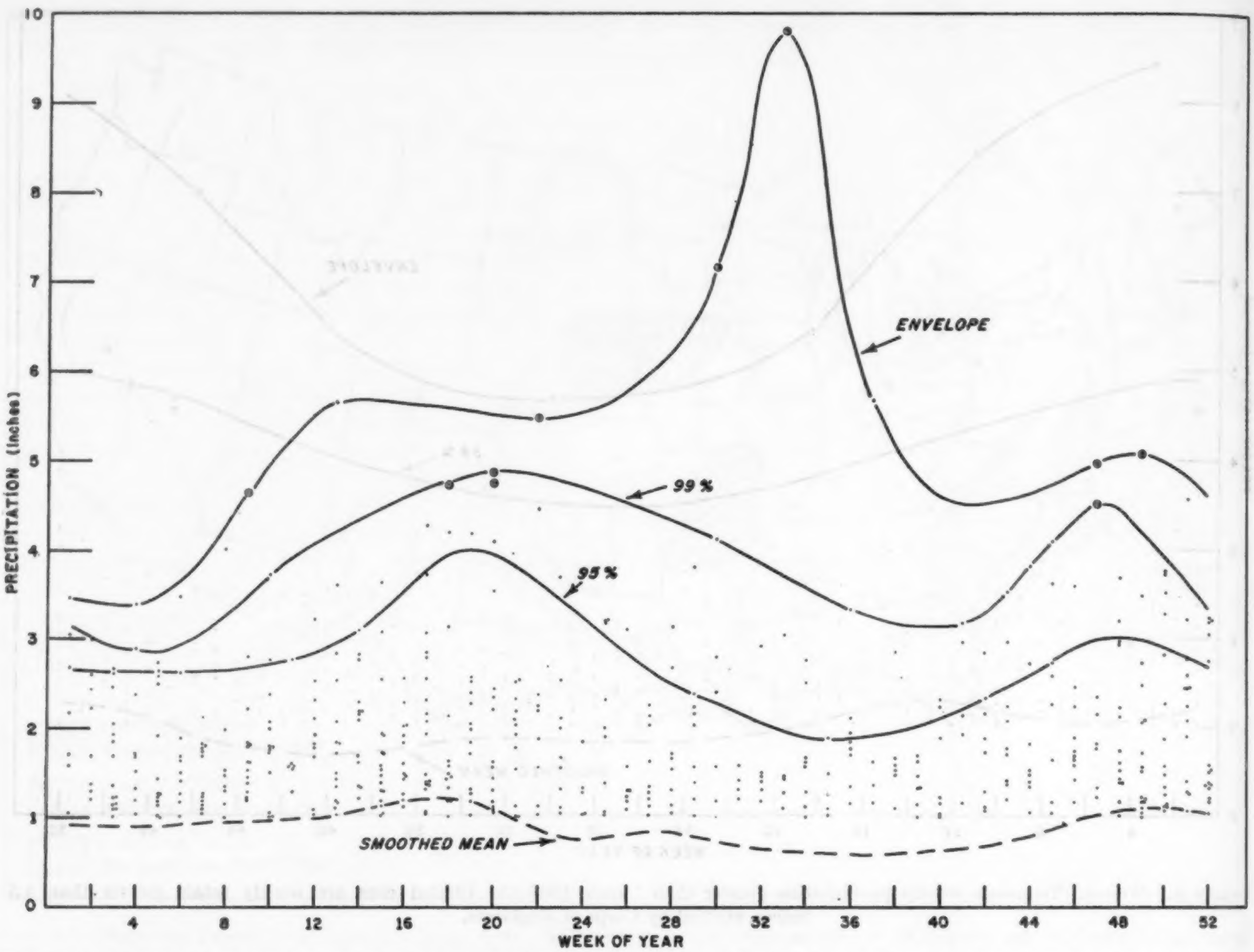


FIGURE 5.—Eastern Texas weekly precipitation greater than 1 inch, 1906–35. Circled dots are weekly totals greater than 4.5 inches, studied by Corps of Engineers.

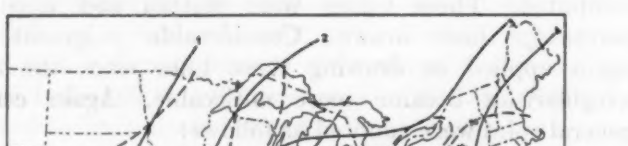


FIGURE 6.—Percent of maximum value of seasonal variation of precipitation over large areas (dashed lines) and index of intense precipitation in inches (solid lines) for the week January 8–14.

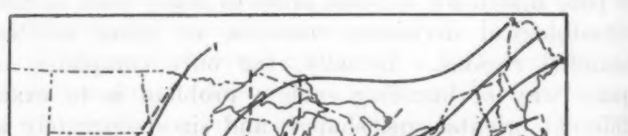


FIGURE 7.—Week of January 22–28.

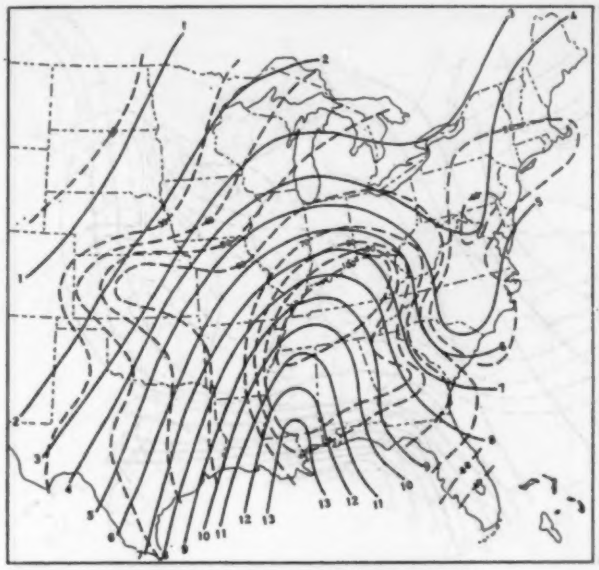


FIGURE 8.—Week of February 5–11.

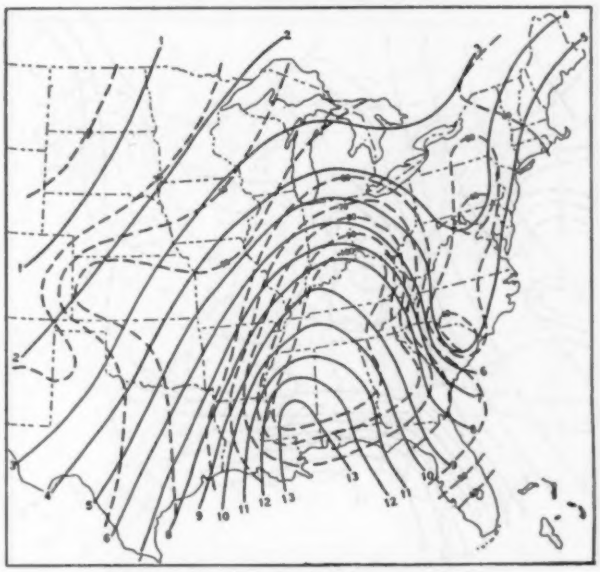


FIGURE 9.—Week of February 19–25.

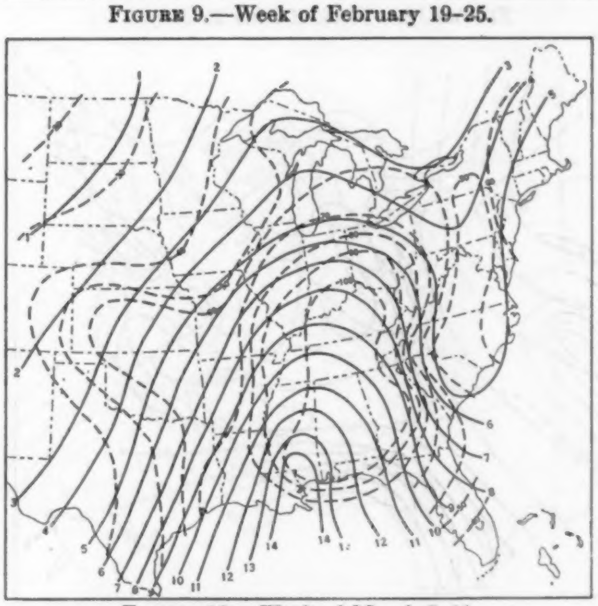


FIGURE 10.—Week of March 5–11.

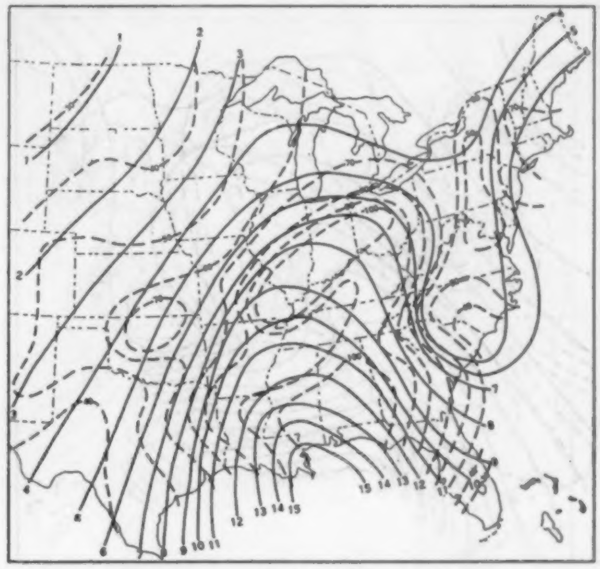


FIGURE 11.—Week of March 19–25.

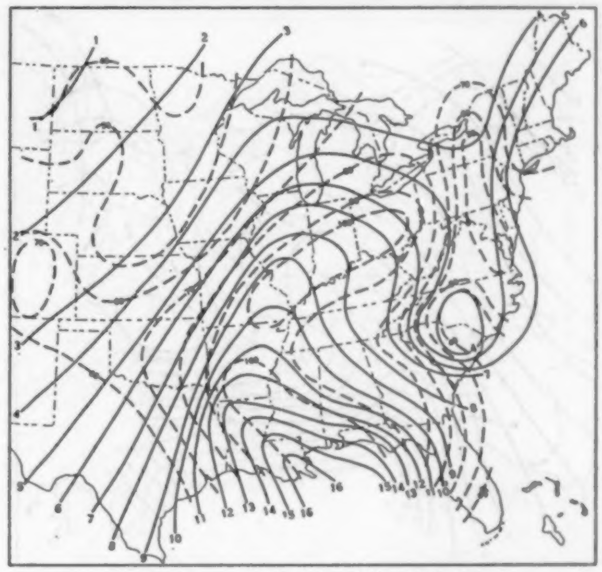


FIGURE 12.—Week of April 2–8.

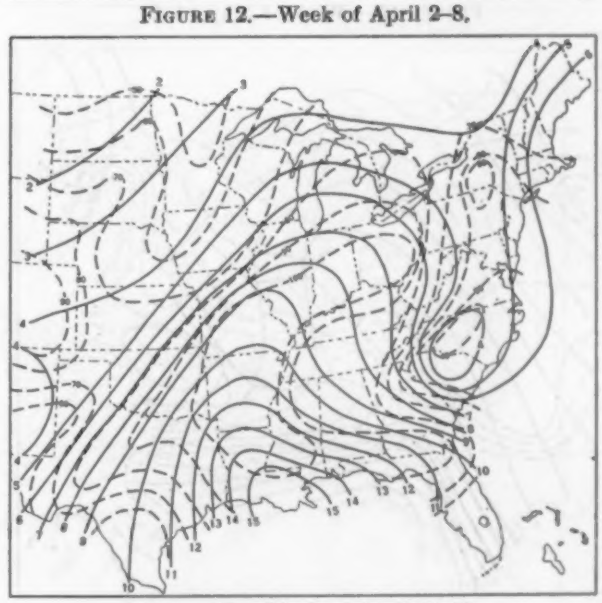


FIGURE 13.—Week of April 16–23.

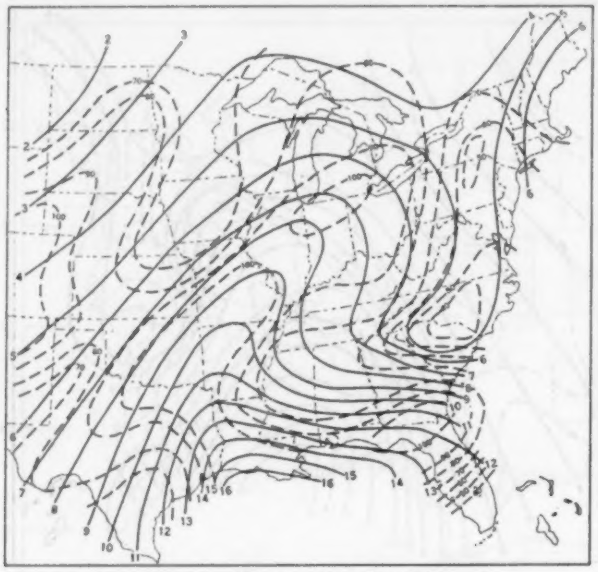


FIGURE 14.—Week of April 30–May 6.

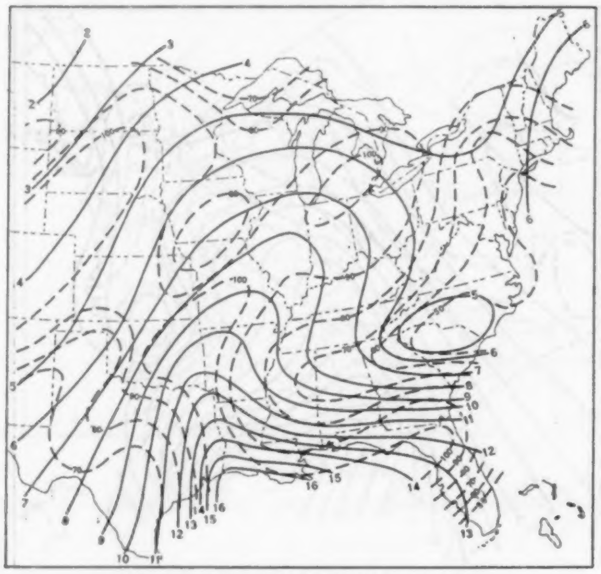


FIGURE 15.—Week of May 14–20.

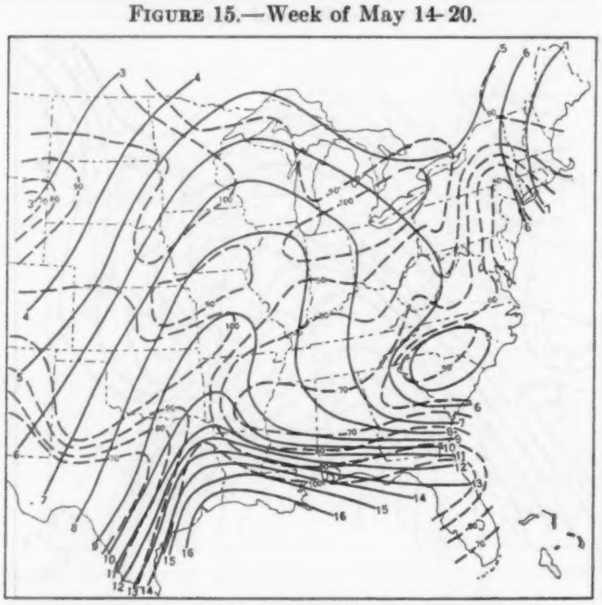


FIGURE 16.—Week of May 28–June 3.

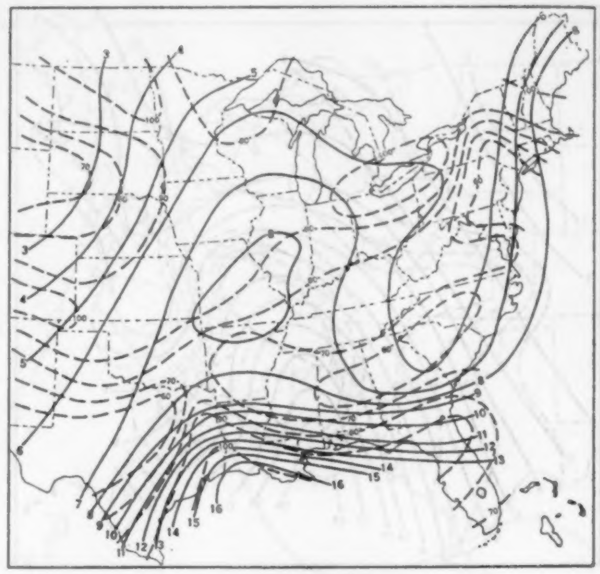


FIGURE 17.—Week of June 11–17.

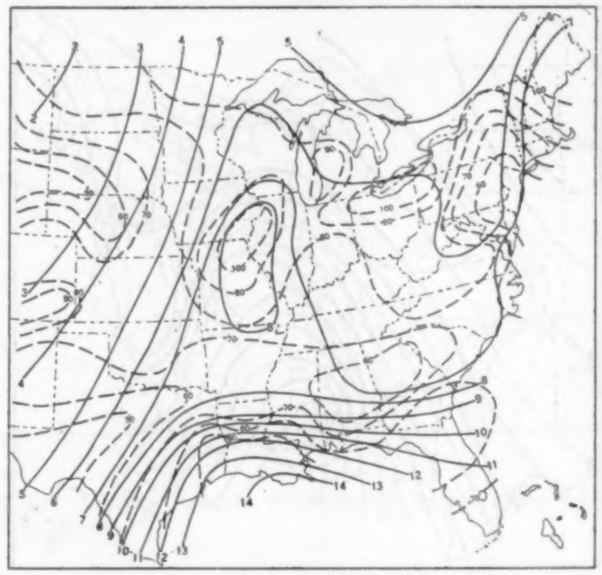


FIGURE 18.—Week of June 25–July 1.

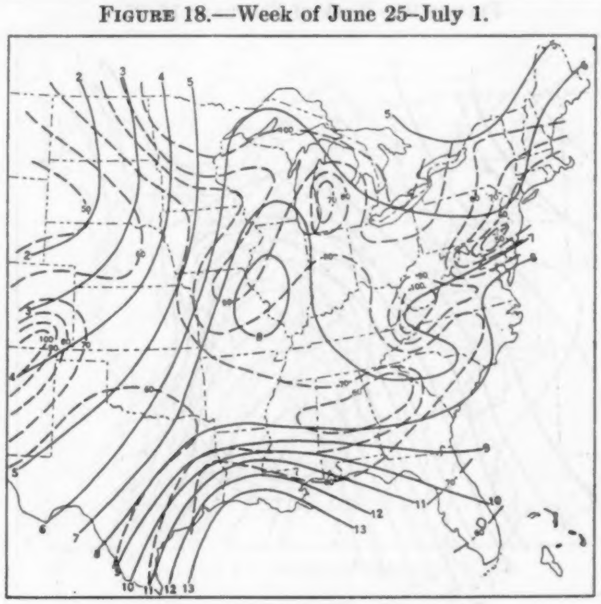


FIGURE 19.—Week of July 9–15.

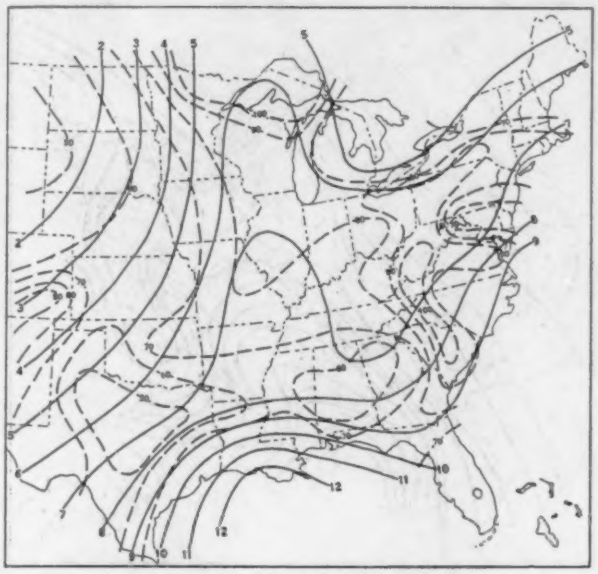


Figure 20.—Week of July 23–29.

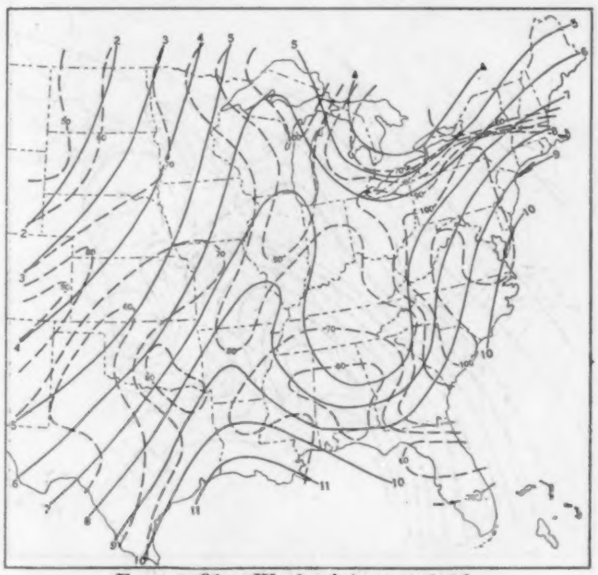


Figure 21.—Week of August 6–12.

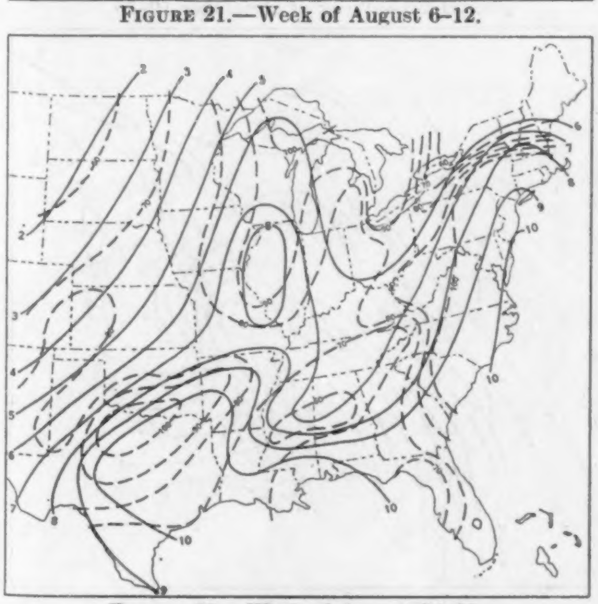


Figure 22.—Week of August 20–26.

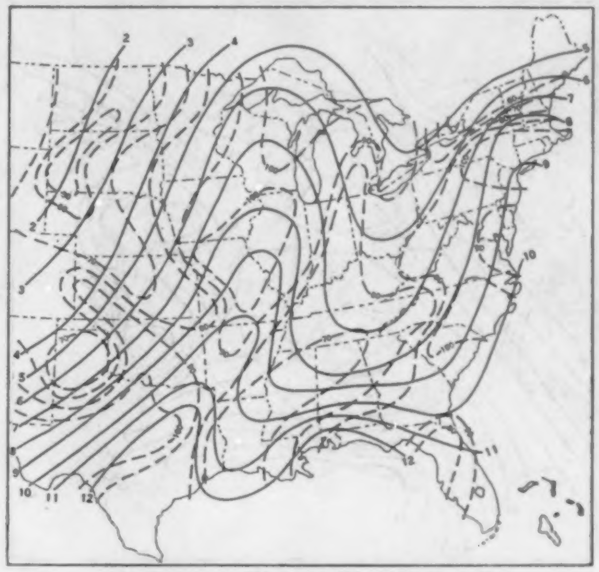


Figure 23.—Week of September 3–7.

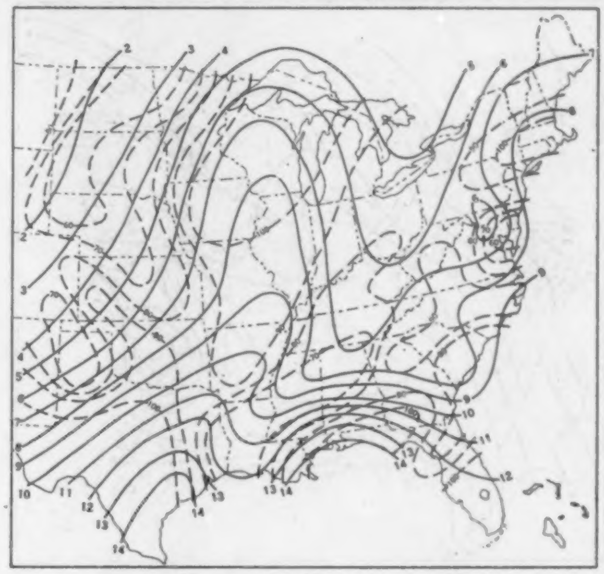


Figure 24.—Week of September 17–23.

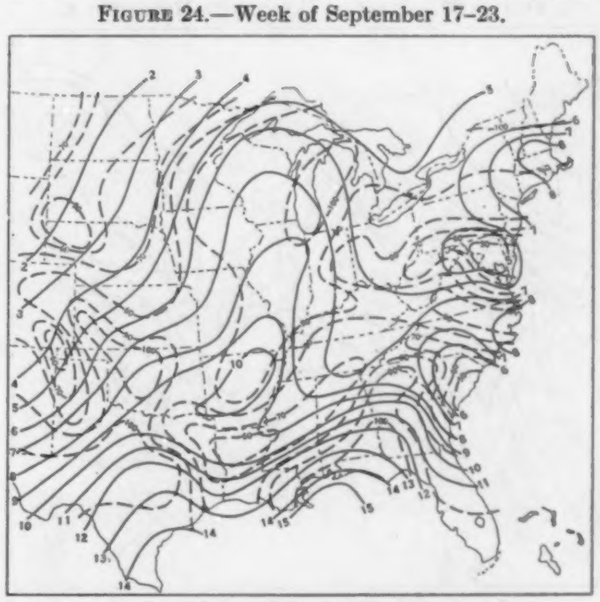


Figure 25.—Week of October 1–7.

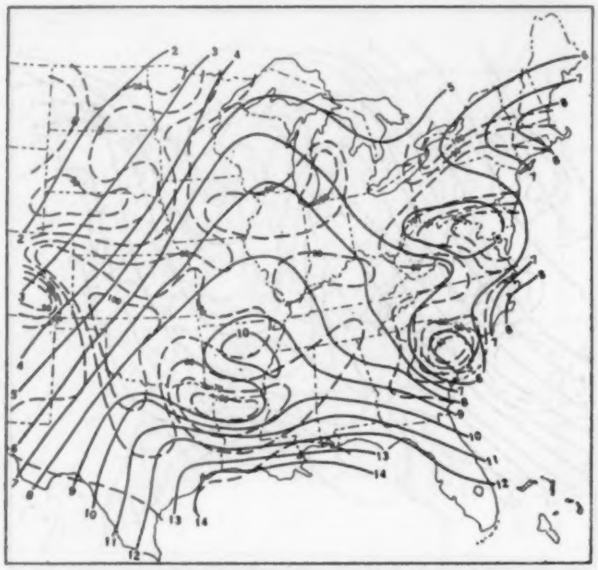


Figure 26.—Week of October 15–21.

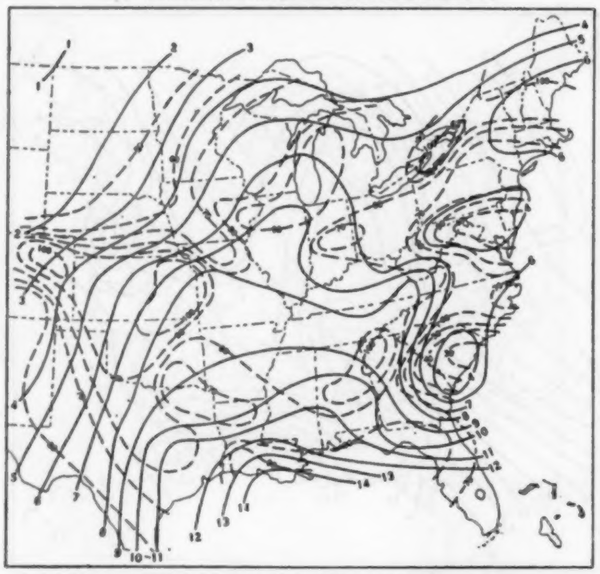


Figure 27.—Week of October 29–November 4.

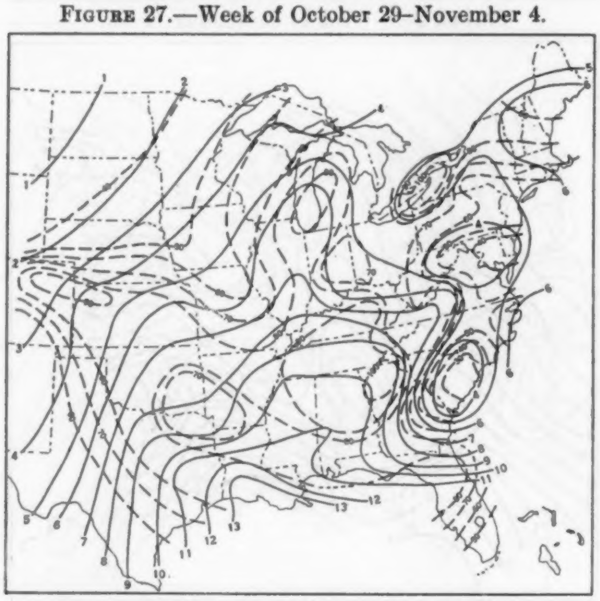


Figure 28.—Week of November 12–18.

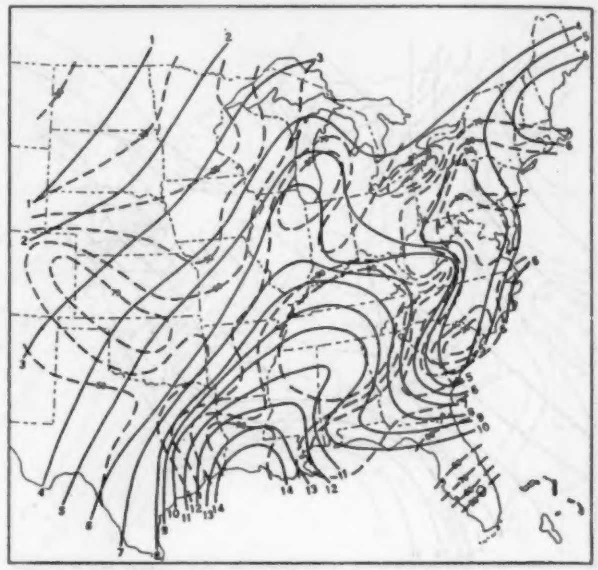


Figure 29.—Week of November 26–December 2.

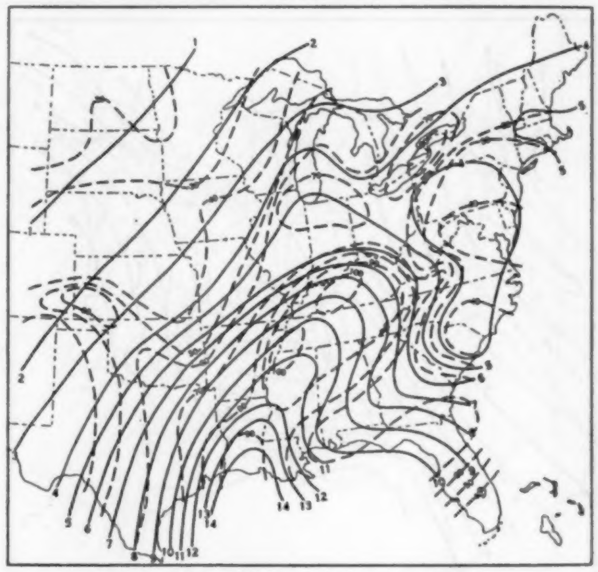


Figure 30.—Week of December 10–16.

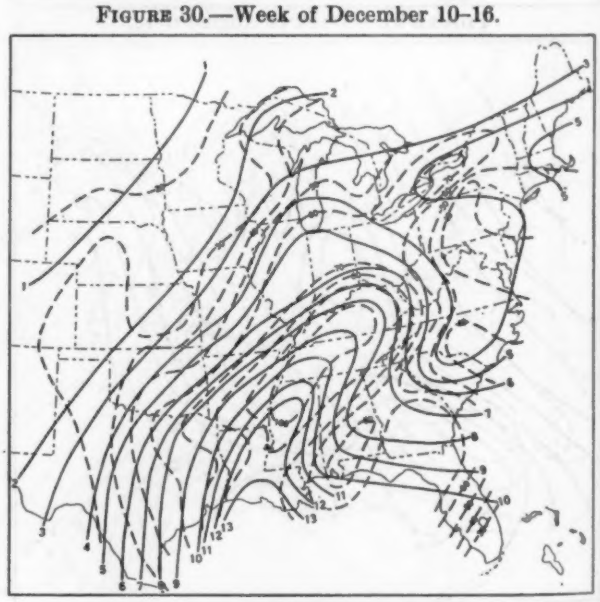


Figure 31.—Week of December 24–31.

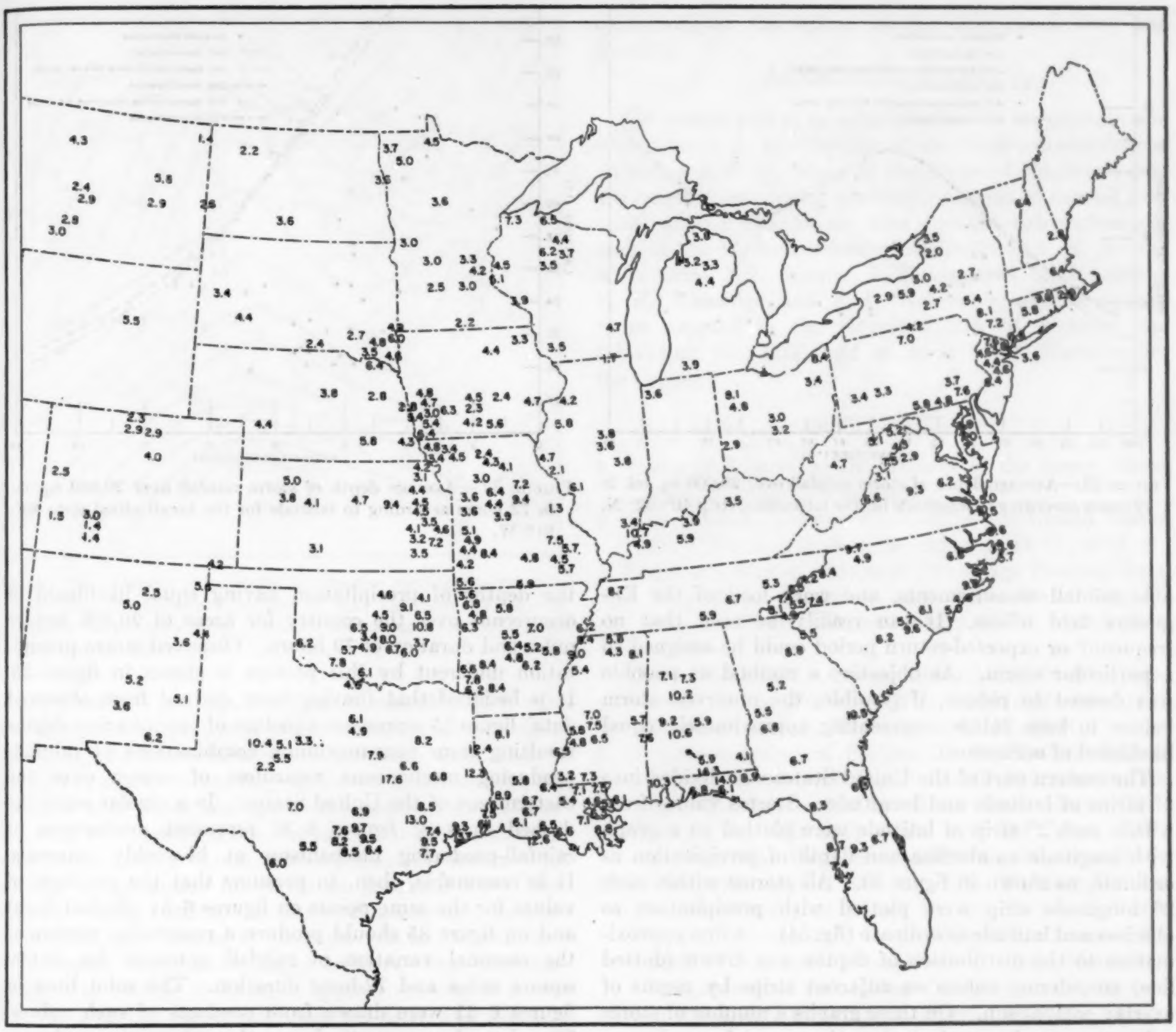


FIGURE 32.—Storm Rainfall. Average depth of precipitation over 20,000 sq. mi. in 72 hours. (From Corps of Engineers Storm Studies.)

3. Experience with major storm studies of the Corps of Engineers Storm Study Program with regard to season and place of occurrence of major storms influenced the final drawing of isolines when doubt existed.

4. From a practical and safety viewpoint there was a tendency to overdraw rather than underdraw percentages. For example, values of 95–100 percent may have been encircled by the 100 percent line in order to catch peaks which might fall to either side of the bi-weekly chart dates.

3. EMPIRICAL INDEX OF SEASONAL VARIATION OF PRECIPITATION

So far, a portayal of the seasonal variation of weekly precipitation over moderately large areas in terms of percentage of a maximum value has been established. The next step was to evaluate a base for maximum values at particular locations. Figure 32 is a plot of all observed 20,000-square-mile, 72-hour storm values from the Corps of Engineers storm studies regardless of season of occurrence. These values can serve as a base for maximum values provided a suitable portayal of areal variation can be obtained. The monumental proportions of a storm study program with the intent of obtaining a complete array of storm values for all areas of the country and all seasons of the year has precluded this method of approach. It should be noted that the selection of storms studied in the program is based upon intensities, total volume of rainfall, associated floods, availability of suit-

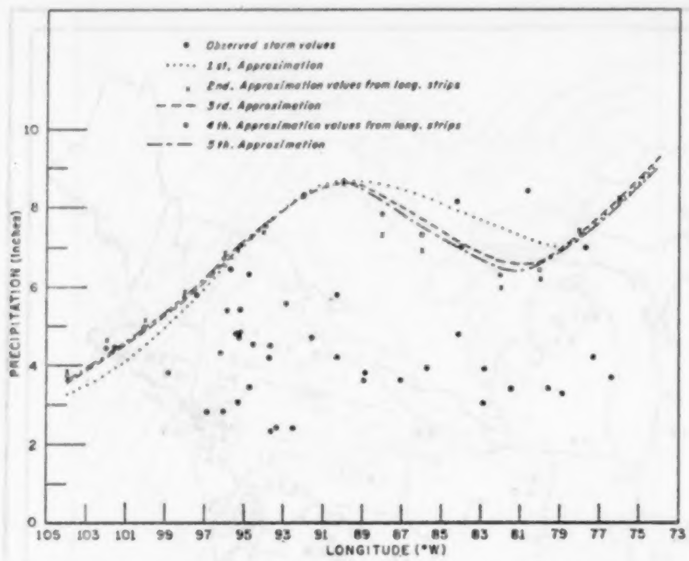


FIGURE 33.—Average depth of storm rainfall over 20,000 sq. mi. in 72 hours according to longitude for the latitudinal strip 40°–42° N.

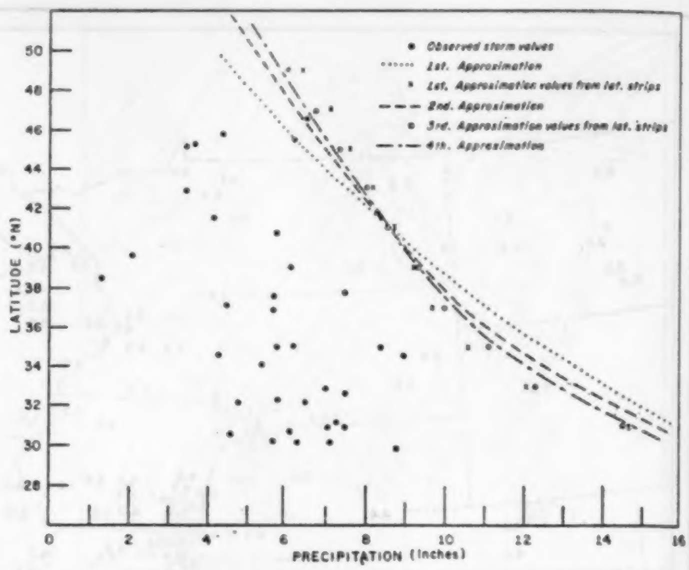


FIGURE 34.—Average depth of storm rainfall over 20,000 sq. mi. in 72 hours according to latitude for the longitudinal strip 89°–91° W.

able rainfall measurements, and work load of the Engineers field offices. It can readily be seen that no frequency or expected-return period could be assigned to a particular storm. As objective a method as possible was desired to reduce, if possible, the observed storm values to base values representing approximately equal likelihood of occurrence.

The eastern part of the United States was divided into 2° strips of latitude and longitude. Storms values from within each 2° strip of latitude were plotted on a graph with longitude as abscissa and depth of precipitation as ordinate, as shown in figure 33. All storms within each 2° longitude strip were plotted with precipitation as abscissa and latitude as ordinate (fig. 34). A first approximation to the distribution of depths was drawn (dotted line) considering values on adjacent strips by means of overlay comparison. On these graphs a number of storm values were undercut since the values were far and away greater than all other values in the neighborhood. One limitation placed upon undercutting was that the storms undercut be fairly evenly distributed over the country. Values read from the visually fitted curves of latitudinal strips were than plotted on the longitudinal strips (X's). Curves of second approximation (dashed lines) were then drawn, roughly splitting the difference between the first approximation and the points obtained from the latitudinal strips. From the dashed lines on the longitudinal strips, then, values were plotted on the latitudinal strips (X's), providing a basis for a third approximation on the latitudinal strips. Additional approximations reduced the remaining differences to the order of several tenths of an inch which was considered a sufficient degree of accuracy.

Values taken from the very last approximation were then plotted on a map and a smooth pattern (fig. 35) was obtained which, it is believed, represents, approximately, the depths of precipitation having equal likelihood of occurrence over the country for areas of 20,000 square miles and duration of 72 hours. Observed storm precipitation undercut by this pattern is shown in figure 35. It is believed that (having been derived from observed data) figure 35 represents a picture of precipitation depths resulting from near-maximum combinations of rainfall-producing mechanisms regardless of season over the eastern part of the United States. In a similar sense the dashed lines of figures 6–31 represent evaluations of rainfall-producing mechanisms at bi-weekly intervals. It is reasonable, then, to presume that the products of values for the same points on figures 6–31 (dashed lines) and on figure 35 should produce a reasonable picture of the seasonal variation of rainfall potential for 20,000 square miles and 72-hour duration. The solid lines in figures 6–31 were drawn from products of such values. They have been smoothed once through seasons and once for area at each season. Additional smoothings would result in minor changes in various portions of the charts but the generalized procedures followed in the development of the charts would belie the accuracy obtained by additional smoothings.

4. DISCUSSION

There were many interesting meteorological questions raised during the drawing of these charts: for example, the apparent short-lived period of intense rain of hurricane origin along the Middle Atlantic Coast, the influence of the Great Lakes on storms of large area and long duration, the northward migration of zones of intense rainfall during the spring, and what appears to be a double structure of areas of intense precipitation in May and June. Synoptic climatological studies of storms would very likely yield indications of the more direct causes of such variations.

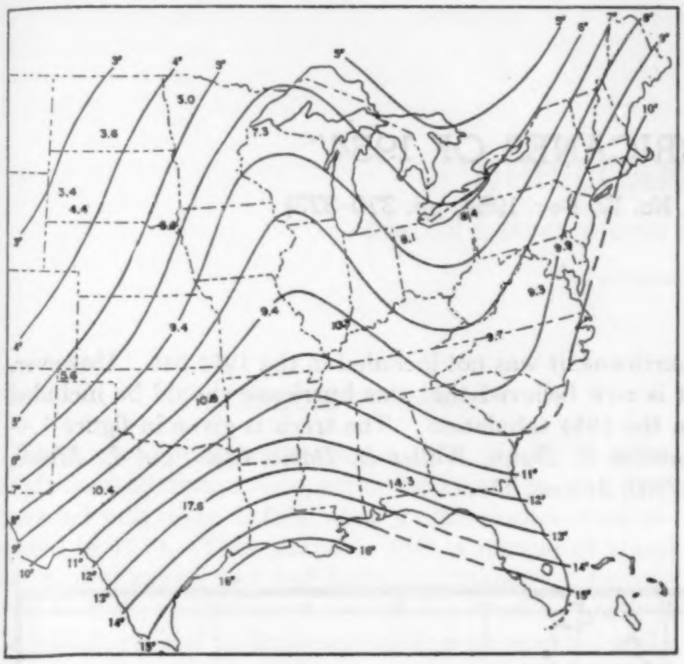


FIGURE 35.—Depths of precipitation having approximately equal likelihood of occurrence; 20,000 sq. mi., 72 hours, all seasons. Plotted values show total rainfall amounts for storms which are undercut by the index.

For a number of years the Hydrometeorological Section has applied a technique of storm transposition to extend effectively the storm history of a particular area. On the basis of synoptic climatology limits are drawn delineating the area over which the apparent significant factors contributing to the mechanism of a particular rainstorm could reasonably occur. Areal transpositions of storms with suitable adjustments for moisture potential have been made in many studies, but temporal transpositions have arbitrarily been limited to 15 days. As an indication of adjustments required for either areal or temporal transposition of storms, or both, it appears reasonable to use the ratio of the index values at the time and place of occurrence to the values at the transposed time and location.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the suggestions and criticisms of J. F. Appleby of the Hydrometeorological Section and D. E. Nunn of the Corps of Engineers who are currently analyzing seasonal variation of rainfall over small areas. Thanks are also due the sub-professional staff of the Hydrometeorological Section—A. E. Brown, A. L. Criss, J. L. Kiester, J. T. Lindgren, C. G. Ludwig, H. H. Vinnedge and F. C. Robrecht—who at various times assisted in the laborious task of plotting and tabulating the data, and to Miss M. I. Hammer for the typing.

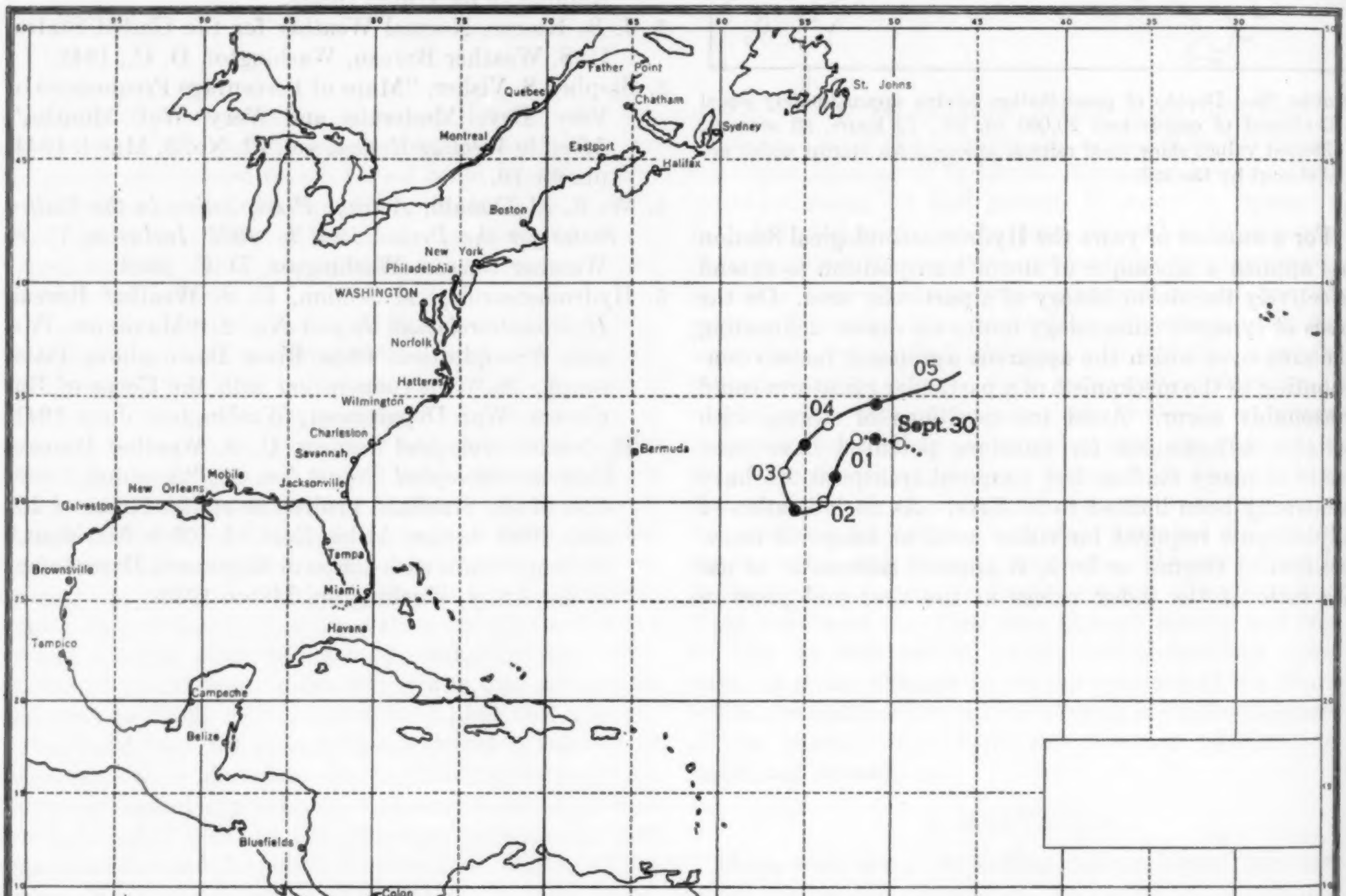
REFERENCES

1. Corps of Engineers, Department of the Army, *Storm Rainfall in the United States.*
2. J. B. Kincer, Normal Weather for the United States, U. S. Weather Bureau, Washington D. C., 1943.
3. Stephen S. Visher, "Maps of Percentage Frequencies of Very Dry, Moderate and Very Wet Months," *Monthly Weather Review*, vol. 72, No. 3, March 1944, pp. 63–70.
4. W. F. McDonald, *Average Precipitation in the United States for the Period 1906 to 1935 Inclusive*, U. S. Weather Bureau, Washington, D. C., 1944.
5. Hydrometeorological Section, U. S. Weather Bureau *Hydrometeorological Report* No. 2, "Maximum Possible Precipitation, Ohio River Basin above Pittsburgh, Pa." In cooperation with the Corps of Engineers, War Department, Washington, June 1941.
6. Hydrometeorological Section, U. S. Weather Bureau, *Hydrometeorological Report* No. 29, "Seasonal Variation of the Standard Project Storm for Areas of 200 and 1000 Square Miles East of 105th Meridian," In cooperation with Corps of Engineers, Department of the Army, Washington, March 1953.

ADDENDUM TO "HURRICANES OF 1954"

***(Monthly Weather Review*, vol. 82, No. 12, Dec. 1954, pp. 370–373)**

To complete the hurricane record of 1954, the hurricane in mid-Atlantic during the period of September 30–October 5, 1954, should be included. It was not given a name at the time, because it was obvious that it would not move any great distance toward the west. As an un-named hurricane, it was not included in the 1954 list. However, it is now believed that this hurricane should be included in the 1954 tabulation. The track is given in figure 1.—*Gordon E. Dunn, Walter R. Davis, and Paul L. Moore, WBO, Miami, Fla.*



HURRICANES OF 1955

GORDON E. DUNN, WALTER R. DAVIS, AND PAUL L. MOORE

Weather Bureau Office, Miami, Fla.

1. GENERAL SUMMARY

There were 13 tropical storms in 1955, (fig. 9), of which 10 attained hurricane force, a number known to have been exceeded only once before when 11 hurricanes were recorded in 1950. This compares with a normal of about 9.2 tropical storms and 5 of hurricane intensity. In contrast to 1954, no hurricanes crossed the coastline north of Cape Hatteras and no hurricane winds were reported north of that point. No tropical storm of hurricane intensity affected any portion of the United States coastline along the Gulf of Mexico or in Florida for the second consecutive year. Only one hurricane has affected Florida since 1950 and it was of little consequence. However, similar hurricane-free periods have occurred before.

Namias and C. Dunn [1] have advanced a hypothesis for the above-normal frequency of hurricanes in 1955:

> . . . planetary wave forms over the North Atlantic evolved in a manner which the authors have come to associate with tropical storm formation. Thus in late July the ridge of the Azores upper level anticylcone thrust strongly northeastward into Europe, thereby introducing a northeasterly flow which, through vorticity flux, led to an anomalously sharp and deep trough extending along the Spanish and African coasts. It was probably at the base of this trough that Connie developed—its formation encouraged by the injection of cyclonic vorticity from the north and by associated vertical destabilization processes as discussed in an earlier report [2]. If this hypothesis is correct, the frequency of tropical storms of the Cape Verde type may well depend upon the degree of development or suppression of the protruding Azores ridge to the north.

It is interesting to note that Garriott [3] almost 50 years ago, with no upper air data, gave a strikingly similar explanation:

> Tropical storm development was exceptionally active in American waters during September 1906. In seeking the causes of this activity, we find an apparent contributory condition in the distribution of atmospheric pressure over the region of observation. In the West Indies and adjacent waters barometric pressure was unusually low, while in the more northern latitudes of the Atlantic, and more especially from the Azores over the British Isles, the barometer averaged above normal, and after the 17th was remarkably high. This arrangement of air pressure overlying the Atlantic naturally produced an unusually strong flow of air from the more northern latitudes toward the Tropics, and in this accelerated movement of air currents is found a recognized associated cause of tropical storm development.

The 1955 hurricanes showed a preferred area of development to the east of the Antilles and to some extent a grouping in their paths. The three hurricanes entering the United States all crossed the North Carolina coast within a 6-week period and three more crossed the Mexican coast within 150 miles of Tampico within a period of 25 days.

The hurricane season of 1955 was the most disastrous in history and for the second consecutive year broke all previous records for damage. Hurricane Diane was undoubtedly the greatest natural catastrophe in the history of the United States and earned the unenviable distinction of "the first billion dollar hurricane". While the Weather Bureau has conservatively estimated the direct damage from Diane at between $700,000,000 and $800,000,000, indirect losses of wages, business earnings, etc., would bring the total over one billion dollars. The total loss of life and damage from Atlantic hurricanes in 1955 is estimated by the Weather Bureau at 1,518 or more killed and $1,053,410,000 damage of which 218 fatalities and $889,310,000 occurred in the United States. The figures for total damage are admittedly incomplete. The latest United Press tabulation of damage at time of preparation of this article was $1,680,200,000 in the United States and $401,200,000 outside the United States, which adds up to a staggering total in excess of two billion dollars. The number of 1,518 or more killed in and outside the United States is the greatest since 1942 when the Weather Bureau began recording this datum.

2. INDIVIDUAL HURRICANES

The individual hurricanes of 1955 are summarized briefly and Connie, Diane, and Janet are discussed in some detail. For additional data, readers are referred to *Climatological Data, National Summary*, Annual 1955 (not yet released).

Alice, December 30–January 5.—A low pressure system of extra-tropical or tropical nature was noted some 600 miles northeast of the Leeward Islands on December 30, and on January 1 it reached hurricane intensity with definite tropical characteristics. It moved on a west-southwestward course passing through the Leeward Islands on January 2. An estimated wind of 75 m. p. h. was reported at St. Kitts and the last observation from St. Barthélemy indicated wind speeds ranging from 69 to 81 m. p. h. Winds of hurricane intensity were observed

at other points. On January 3 aircraft reconnaissance reported maximum winds of 86 m. p. h. and a dropsonde in the eye confirmed the warm-core center. After January 3, the hurricane diminished rapidly in intensity.

Mr. Ralph L. Higgs, Meteorologist in Charge at Weather Bureau Airport Station, San Juan, P. R., reports as follows:

This storm has aroused considerable interest. People were somewhat skeptical and slow in believing that a hurricane had actually formed. Already historians have expressed their opinion as to whether this was, or was not, the first of its kind in this area. In Puerto Rico a controversy centers about a storm that affected this island in the year 1816; one historian maintaining that it occurred in the month of January while another holds that it occurred in September. Reports from other islands mention a winter storm that affected the region many years ago. It appears that wintertime storms have been observed in these areas before. It is doubtful, however, whether any of them ever attained the intensity of "Alice" of 1955. It can be said of great certainty that this storm was definitely the first of its kind, at least, in the last 100 years.

The records do indicate, however, that a winter hurricane of somewhat similar origin passed through the Leeward Islands on March 8, 1908, with Basseterre, St. Kitts, reporting a minimum pressure of 29.28 inches. Columbus described several of the winter storms encountered by him on his journeys to the New World as "hurricanes". Brooks [4], however, has found they were probably normal winter storms. Occasional winter hurricanes do occur in the Pacific Ocean and tropical Lows are more rarely observed in the Atlantic, but it is most unusual for one of the latter to reach full hurricane intensity during the winter season. Possibly this may be another consequence of the general warming observed during the past several decades.

There was no loss of life from Alice and damage is estimated at around $100,000. The rainfall was beneficial in Puerto Rico where it alleviated a dry period which had persisted since the middle of the previous October.

Brenda, July 31–August 2.—Tropical storm Brenda formed in the north-central Gulf of Mexico on July 31 and crossed the coastline east of New Orleans on the afternoon of August 1. It was attended by rains of 4 inches or more from Pensacola westward to Lake Charles, and by winds of 50 m. p. h. at Shell Beach on the south side of Lake Borgne where the tide rose to 5 to 6 feet above normal. Two lives were lost in the Mobile area but total damage was small.

Connie, August 3–13.—Hurricane Connie set the stage for one of the most disastrous and costly floods of record in the northeastern States. The hurricane's slow movement on the 10th, 11th, and 12th resulted in heavy rainfall from North Carolina northward across the northeastern States to the interior of New England. The rains did not let up until the dying remnants of the hurricane had moved into the Great Lakes region on the 14th. The rainfall amounted to 2 to 8 inches in eastern North Carolina and ranged upward to 10 to 12 inches from the Chesapeake Bay area to extreme southern New York.

The first indications of hurricane Connie were noted on the morning of August 3 when the SS *Mormacreed* reported unusually strong westerly winds and showery, squally weather between Latitudes 5° and 10° N. and Longitudes 50° and 55° W. At the same time another ship, the *African Sun*, passed through a strong easterly wave in the vicinity of Latitude 16° N. and Longitude 45° W. The SS *Bonaire* reported a pressure of 996.2 mb. (29.42 inches) and a wind of east-northeast force 8 at 2200 EST of the 3d, providing the first indication that a strong vortex had formed in the northern end of the easterly wave. Earlier in the day, there were some indications of a vortex in the southern end but the principal cyclogenesis took place in the top end of the wave, as is usually the case, and hurricane Connie was born. The irregular Cape Verde reports provide no evidence of any unstable wave passing through the area in which Connie might later have developed. Reconnaissance aircraft on the 4th reported the eye at Latitude 15.8° N. and Longitude 52.8° W., with a false radar eye about 75 miles northeast of this position. Highest wind observed was 55 knots in the northeast quadrant. As it turned out, the false eye proved to be the real vortex which developed rapidly into hurricane Connie.

The storm moved west to west-northwest at 14 to 16 m. p. h., gradually increasing in size and intensity, and, by the morning of the 5th, maximum winds were estimated at 125 m. p. h. with a central pressure of 985 mb. (29.09 inches). The hurricane center passed some 40 to 50 miles north of the northern Leeward Islands and Puerto Rico, attended by gale winds with peak gusts of 80 to 100 m. p. h. and moderately heavy rains in the islands. On August 7 the eye was described by the observer as being shaped like an inverted cone, with the calm area less than 8 miles in diameter at the surface and 38 miles across at 18,000 feet. Maximum surface wind at this time was estimated at 145 m. p. h., and lowest pressure was 952 mb. (28.11 inches) measured by dropsonde. On the next day, the central pressure had diminished to 944 mb. (27.88 inches) the lowest during the life of the hurricane, as it moved northwestward some 200 to 250 miles east of the Bahama Islands. The hurricane slowed to 6 to 8 m. p. h. in forward speed 400 to 500 miles off the northeastern coast of Florida, and central pressure had filled to 954 mb. (28.17 inches) by the afternoon of the 9th, and to 977 mb. (28.85 inches) by the morning of the 10th. Penetration during the 10th indicated the eye was becoming filled with clouds and poorly defined. Connie drifted slowly toward the west-northwest and west on the 9th and 10th, turned toward the north on the night of the 10th, and north-northeast late on the 11th. It then turned northward again on the 12th as it passed inland on the North Carolina coast near Morehead City. At Wilmington, N. C., the fastest measured mile was 72 m. p. h., and the peak gust was 83 m. p. h. during the evening of the 11th as the hurricane passed about 100 miles to the southeast and east of the station. Winds

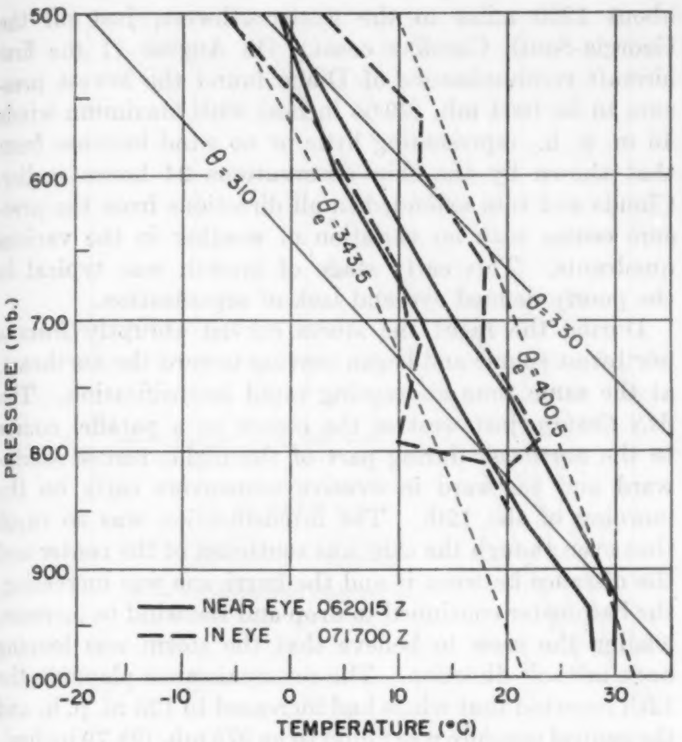


FIGURE 1.—Dropsondes in hurricane Connie, August 6 and 7, 1955.

of 75 m. p. h. with peak gusts of 100 m. p. h. and lowest pressure of 962 mb. (28.40 inches) were reported at Fort Macon, N. C., near the point where the hurricane crossed the coastline. However, it has not been established whether this was a measured or an estimated speed.

Tornadic activity was reported in the Carolinas during the afternoon and evening of August 10, while the hurricane was about due east of the Georgia coast, and before the winds had increased to strong along the Carolina coasts. One tornado occurred in North Carolina at Penderlea in northern Pender County and five others were reported in South Carolina from Georgetown northward. These tornadoes were reported as moving from east to west.

Beach erosion on the North Carolina coast was considerable, as tides rose to as much as 7 feet above normal from Southport to Nags Head, and to 5 to 8 feet above normal in the sounds at the mouths of the rivers. Total damage in North Carolina was estimated at $40 million, of which about three-fourths was crop damage. The hurricane caused no deaths or serious injuries in North Carolina.

The slow and somewhat meandering course of Connie and the loss of intensity while off the south Atlantic coast for a 48- to 72-hour period from late on the 8th to early on the 11th were the principal forecast problems during the life of the storm. Synoptically, on August 8, a strong (1027 mb.) surface high pressure system was located over the eastern Atlantic with a ridge extending to the middle Atlantic coast. At the 500-mb. level the picture was rather similar, with the ridge aloft along the Atlantic

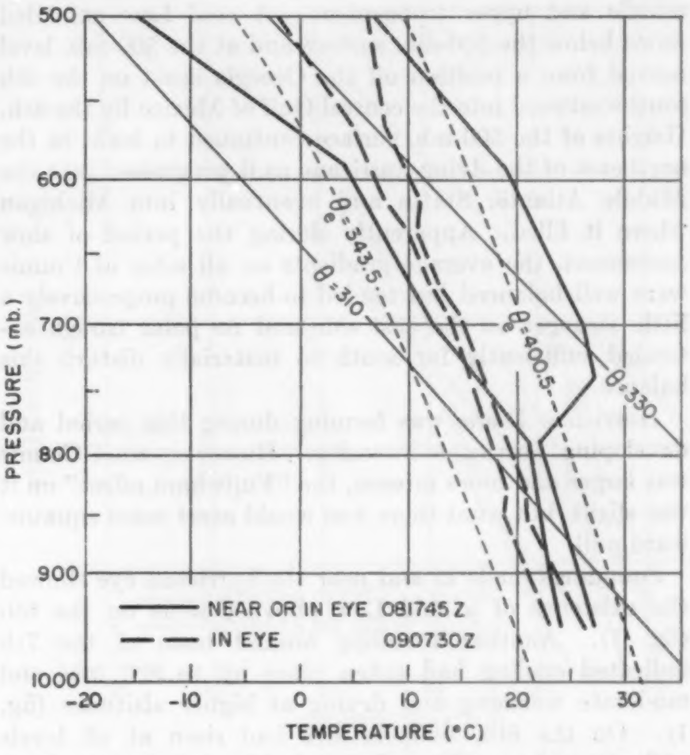


FIGURE 2.—Dropsondes in hurricane Connie, August 8 and 9, 1955.

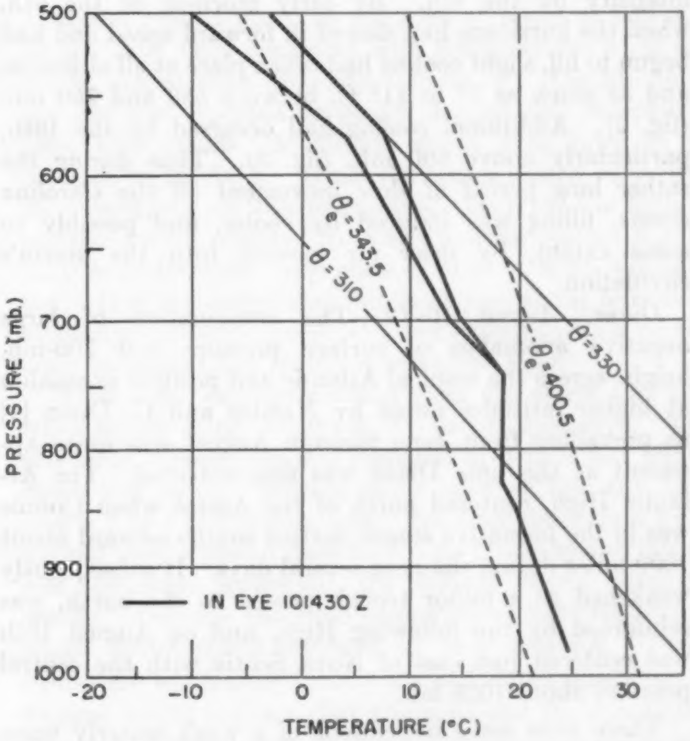


FIGURE 3.—Dropsonde in eye of hurricane Connie, August 10, 1955.

coast tending to move slowly northward with time. Several rather weak polar troughs moved eastward over northern latitudes with little effect in the latitude of and the area immediately to the north of the hurricane. The situation in the sub-Tropics was more complicated in the

middle and upper troposphere. A cold Low extended down below the 500-mb. surface and at the 500-mb. level moved from a position off the Georgia coast on the 6th southwestward into the central Gulf of Mexico by the 8th. Heights of the 500-mb. surface continued to build to the northeast of the dying hurricane as it progressed into the Middle Atlantic States and eventually into Michigan where it filled. Apparently during the period of slow movement, the average gradients on all sides of Connie were well balanced but tended to become progressively a little stronger on the east side and no polar trough extended sufficiently far south to materially disturb this balance.

Hurricane Diane was forming during this period and developing hurricane intensity. However, since Connie was larger and more intense, the "Fujiwhara effect" on it was slight, but what there was would exert some equatorward pull.

Soundings made in and near the hurricane eye showed the existence of a cold Low above Connie on the 6th (fig. 1). Another sounding around noon of the 7th indicated cooling had taken place up to 800 mb. and moderate warming and drying at higher altitudes (fig. 1). On the 8th, temperatures had risen at all levels and as much as 4° to 8° C. with further drying above 800 mb. (fig. 2). The hurricane reached its maximum intensity by the 8th. By early morning of the 9th, when the hurricane had slowed in forward speed and had begun to fill, slight cooling had taken place at all altitudes, and as much as 7° to 11° C. between 550 and 750 mb. (fig. 2). Additional cooling had occurred by the 10th, particularly above 600 mb. (fig. 3). Thus during the rather long period of slow movement off the Carolina coasts, filling was induced by cooler, and possibly to some extent, by drier air moving into the storm's circulation.

Diane, August 10–19.—The combination of large negative anomalies of surface pressure and 700-mb. height across the tropical Atlantic and positive anomalies at higher latitudes noted by Namias and C. Dunn [1] as prevailing from June through August was quite apparent at the time Diane was first detected. The Atlantic High, centered north of the Azores when Connie was in the formative stages, settled southwestward about 1000 miles during the next several days. It subsequently weakened as a minor trough passed to the north, was reinforced by the following High, and on August 10th was centered just east of Nova Scotia with the central pressure about 1028 mb.

There were some indications of a weak easterly wave earlier but the first conclusive evidence of the disturbance that was to become Diane was observed on August 10. Analysis that morning indicated a cyclonic circulation northeast of the Leeward Islands and at 1930 EST ships some 400 to 500 miles from the northernmost islands reported heavy showers and east to southeast winds of 35 to 45 m. p. h. At this time hurricane Connie was about 1200 miles to the west-northwest, just off the Georgia-South Carolina coast. On August 11 the first aircraft reconnaissance of Diane found the lowest pressure to be 1004 mb. (29.65 inches) with maximum winds 46 m. p. h., representing little or no wind increase from that shown by the ship observations 24 hours earlier. Clouds and rain extended in all directions from the pressure center with no variation of weather in the various quadrants. This early stage of growth was typical in the poorly defined eye and lack of organization.

During the night the storm curved abruptly from a northwest course and began moving toward the northeast, at the same time undergoing rapid intensification. The *MS Coburg*, just west of the center on a parallel course to the northeast during part of the night, turned southward and eastward in evasive maneuvers early on the morning of the 12th. The intensification was so rapid that even though the ship was southeast of the center and the distance between it and the hurricane was increasing, the barometer continued to drop and the wind to increase, leading the crew to believe that the storm was looping back in their direction. The reconnaissance plane on the 12th reported that winds had increased to 125 m. p. h. and the central pressure was found to be 975 mb. (28.79 inches). The eye by this time was well defined and 30 miles in diameter. It was described by the observer as resembling an inverted teacup. The weather distribution had become more typical with the northeast quadrant showing more activity than the others. An interesting feature of the reconnaissance was a secondary pressure minimum, at first thought to be the principal center, located 62 miles northeast of the primary eye.

In view of the rapid growth, sudden change in direction, and multiple eye structure, it is interesting to speculate as to what extent factors other than strictly steering currents were involved in the storm's course at this stage. Possibly a process in which more rapid deepening was favored to the northeast of the storm than in other quadrants was partially responsible for the movement. It is likely that the original easterly wave began deepening as it moved under a cold Low (with super-imposed warm air at still higher levels) and that this condition provided added instability for growth and imposed the cyclonic flow of the large scale cold Low on the movement of the smaller warm vortex. Diane followed this cyclonic path (see fig. 9, August 11–13), until August 13 when it became re-established on a more normal west-northwestward course. By this time the developing storm had caused warming through a deep layer, resulting in a weakening of the cold Low and its influence on the hurricane's movement. The possibility of some influence from the "Fujiwhara effect", or tendency for cyclonic rotation of cyclone pairs about a point representing the center of mass, should also be considered here. Diane's erratic movement was at least in general agreement with this effect. A more normal path was resumed when Connie weakened and moved farther north. Once back on the west-north-

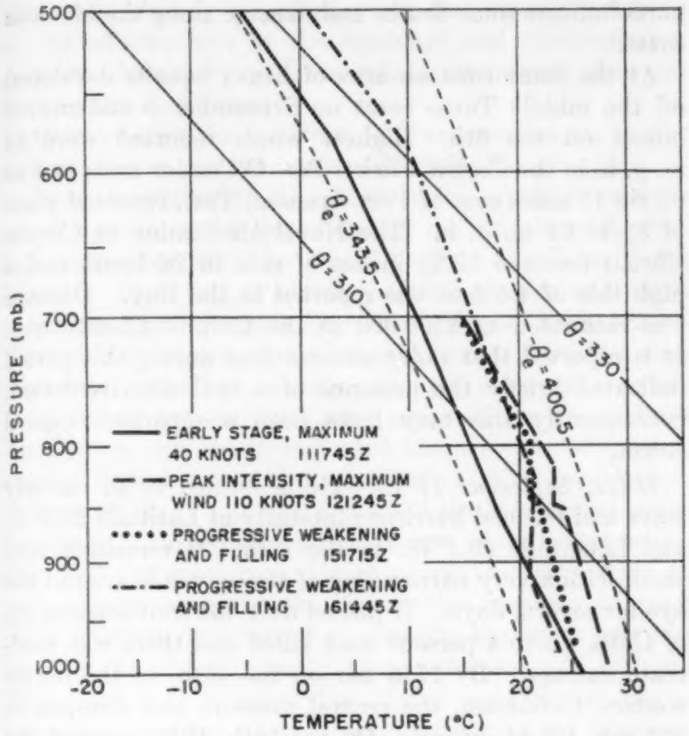


FIGURE 4.—Dropsondes in hurricane Diane, August 11, 12, 15, and 16, 1955.

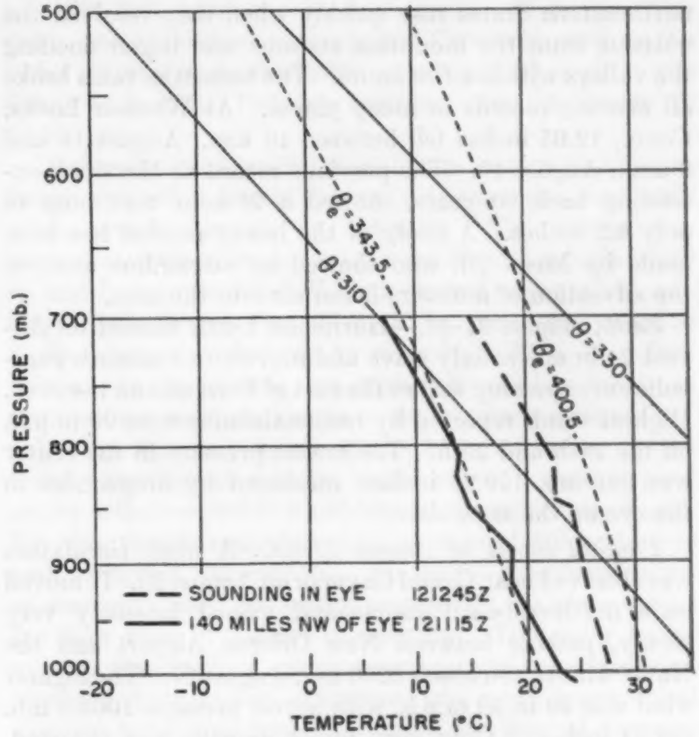


FIGURE 5.—Dropsonde in hurricane Diane, August 12, 1955.

west course, Diane continued to have a fairly regular movement, reaching the North Carolina coast on August 17.

A considerable number of dropsondes were taken during the life history of Diane, providing an excellent opportunity to observe changes in its thermal structure. (See fig. 4.) The first of these was taken on August 11 when development had only begun with maximum winds of 46 m. p. h. and minimum pressure 1004 mb. Some 24 hours later when winds had increased to 125 m. p. h. and minimum pressure had dropped to 975 mb., a dropsonde from 700 mb. showed a 24-hour temperature rise of 3° to 6° C. between that level and the surface. At this time another dropsonde 140 miles northwest of the center (fig. 5) showed temperatures up to 700 mb. to be within about 1° C. of the mean for a large number of soundings at that distance from the center of mature hurricanes (Jordan and Jordan [5]). The asymmetry evidenced in the pressure field by the multiple eyes was also apparent in the temperatures. Comparison of the sounding in the primary eye with one taken in the secondary center 62 miles to the northeast, showed the primary eye to be warmer by as much as 3° to 5° below 800 mb. but 1° colder at 700 mb., indicating greater instability in the dominant eye.

The lowest pressure measured in the storm was 969 mb. (28.62 inches) by dropsonde on August 13. Maximum winds were not measured on that date but 125 m. p. h. was reported on both the 12th and 14th. After the 13th a tendency for slight filling began and, coincidental with this, there was a gradual cooling of the layer below about 750 mb. This cooling amounted to about 2° C. by the 15th and ranged up to as much as 4° lower at 900 mb. on the 16th when compared with temperatures when the storm was at peak intensity (see fig. 4). On the 15th, the eye was reported as poorly defined and completely filled with clouds. Maximum winds were down to 86 m. p. h. on the 16th. When the center passed very close to Wilmington on the morning of the 17th, the highest sustained wind reported from any weather station was 50 m. p. h. at Hatteras, with gusts of 74 m. p. h. at Wilmington. It is estimated that winds of just about hurricane intensity were experienced at a few exposed points on the coast between Cape Hatteras and Cape Fear.

While some damage resulted from the storm tide and wave action along the coast, it was not extensive. The tide near Wilmington was reported as 6 to 8 feet above mean low water. Normal range between low and high tide is 3 to 4 feet in this area. No large departures from normal were reported elsewhere. As Diane moved inland and continued northward, the damage figures began to mount. Damage has been estimated at $754,706,000 of which $600,000,000 occurred in New England. These figures are admittedly incomplete and direct plus indirect damage would indicate that Diane earned the appelation of "the first billion dollar hurricane." Approximately 200 persons lost their lives, all from Diane's floods.

The sections worst hit were Pennsylvania, Massachusetts, Rhode Island, Connecticut, and southeastern New York, although there was some serious flooding from North Carolina northward. Much of the loss of life was due to the fact that relatively small river basins in the

northeastern States rose quickly when they received the outpour from the mountain streams and began flooding the valleys within a few hours. The torrential rains broke all existing records in many places. At Windsor Locks, Conn., 12.05 inches fell between 10 a.m., August 18 and 9 a.m., August 19. The previous record at Hartford, extending back 90 years, showed a 24-hour maximum of only 6.2 inches. A study of the heavy rainfall has been made by Mook [6], who showed by streamline analysis the advection of moisture-laden air into the area.

Edith, August 24–31.—Hurricane Edith formed on August 24 in an easterly wave and moved on a smooth parabolic curve passing well to the east of Bermuda on the 29th. Highest winds reported by reconnaissance were 90 m.p.h. on the 28th and 29th. The lowest pressure in the center was 991 mb. (29.26 inches) measured by dropsondes in the eye on the same dates.

Tropical Storm of August 23–29.—A weak circulation was observed near Grand Cayman on August 23. It moved on a northwestward course and gained intensity very slowly, passing between New Orleans Airport and the Naval Air Station about 0200 EST, August 27. The highest wind was 40 to 50 m.p.h. with lowest pressure 1000.3 mb. (29.54 inches). Only very minor damage was reported.

Flora, September 3–9.—An unstable easterly wave passed through the Cape Verde Islands during August 30–31. A message was received on the 30th from Panair du Brazil at Recife, Brazil:

> Tropical storm evident. Cyclonic circulation aloft to 4000 meters. Center approximately 11° N., 21° W. Displacement 18 m. p. h. WNW. Storm associated with easterly wave along ITC [intertropical convergence zone].

This weak circulation was the genesis of Flora which reached hurricane intensity on September 3 at approximately Latitude 21° N. and Longitude 40° W. Hurricane Flora moved on a smooth parabolic path northward through the middle Atlantic, passing some 9° east of Bermuda on the 6th and early on the 7th. The highest wind reported was 104 m.p.h. at 1230 EST on the 8th at Latitude 41.0° N. and Longitude 49.4° W., with central pressure of 972 mb. (28.70 inches). The lowest reported pressure during the storm's history was 967 mb. (28.55 inches) at 31.5° N. and 55.3° W. on the 6th.

Gladys, September 4–7.—This tropical storm formed in the Gulf of Campeche and moved first northwestward and later southward entering the coast of Mexico north of Tampico. Highest wind reported from Tampico was 48 m.p.h. from the northwest but higher winds may have occurred along the coast to the north of Tampico. The lowest pressure reported by reconnaissance was 997 mb. (29.44 inches). Winds of 81 m.p.h. were reported by the reconnaissance plane on one occasion and also by a civilian plane on the same date and, therefore, Gladys has been classified as of hurricane intensity. There was a fairly reliable report of 25 inches of rain in 3 days at Tampico beginning the sequence of hurricane-associated rains which culminated in the Tampico disaster. Meager reports indicate some deaths and damage along the Mexican coast.

At the same time an area of heavy squalls developed off the middle Texas coast on September 5 and moved inland on the 6th. Highest winds reported were 45 m. p. h. in the Corpus Christi-Port O'Connor area, and an oil rig 15 miles east of Port Aransas, Tex., reported gusts of 55 to 65 m. p. h. The Naval Air Station at Corpus Christi received 12.23 inches of rain in 24 hours and a high tide of 4.5 feet was reported in the Bay. Damage was estimated at $500,000 in the Corpus Christi area. It is reported that radar observations during this period indicated briefly the presence of a cyclonic circulation, consequently this may have been a separate tropical storm.

Hilda, September 11–19.—Hilda formed in an easterly wave and reached hurricane intensity at Latitude 20.0°N. and Longitude 69.1°W. on the 12th. It remained very small with a very narrow ring of strong winds around the eye for several days. It passed over the southeastern tip of Cuba where 4 persons were killed and there was moderate damage. By 1730 EST on the 15th, in the northwestern Caribbean, the central pressure had dropped to 963 mb. (28.44 inches). On the 16th, Hilda crossed the Yucatan peninsula midway between Chetumal and Cozumel, an area very sparsely populated.

Hilda reached its greatest intensity in the Gulf of Campeche. The center moved inland early on the 19th at Tampico which experienced a calm for 45 minutes. The lowest pressure at Tampico was 952 mb. (28.11 inches). Highest wind recorded before the anemometer blew away was 105 m. p. h. and the maximum wind was estimated at 150 m. p. h. Newspaper reports indicate 300 deaths and $120,000,000 damage, largely from floods.

Ione, September 11–21.—Ione developed in an easterly wave which passed through the Cape Verdes on September 6 and the circulation was still quite weak on the 11th; but Ione began to develop on this date and reached hurricane intensity during the night of September 14–15 in about Latitude 19.5°N. and Longitude 62.6°W. Ione then pursued a general northwesterly course toward the North Carolina coast. It reached greatest intensity on the 17th when a central pressure of 938 mb. (27.70 inches) was reported with maximum winds of 125 m. p. h. By the time the hurricane reached the North Carolina coastline on the 19th, the central pressure had filled to about 28.35 inches and the maximum winds had decreased slightly. Ione was the third hurricane to pass through eastern North Carolina within six weeks and the fourth within eleven months. Not within the known meteorological history of this section have so many hurricanes affected the area within so short a period. Total storm damage, mostly to crops in eastern North Carolina, is estimated at $88,035,000. There were 7 fatalities directly or indirectly attributable to the hurricane. The lack of any deaths from Connie and Diane in North Carolina and only 7 in Ione and the comparatively small property

damage, excluding crop damage, in this area, is a tribute to the effectiveness of the warnings and precautionary measures taken by governmental and private agencies such as the Red Cross.

After crossing the coastline, Ione recurved to the northeast passing out to sea south of Norfolk, Va.

Janet, September 21–29.—Most of the easterly waves in which hurricanes developed during the months of August and September could be traced back to the Cape Verde Islands. However, at about the time the easterly wave in which Janet eventually formed should have passed through the Cape Verdes, receipt of reports from this area was so irregular that no early history of the wave is available. Early on the 21st, pilot reports from the airlines Air France and Iberia indicated the presence of a weak tropical disturbance at about Latitude 13.5° N. and Longitude 53.0° W. It is the experience of the Miami Hurricane Center that almost all tropical storms of hurricane intensity, and the great majority of minor tropical storms as well, cannot pass across the New York-Capetown shipping route without detection. Apparently the wave was too weak to be noted between Longitudes 40° and 50° W. Therefore, it is believed that Janet was just attaining hurricane intensity when encountered by the *SS Mormacdale* in Latitude 13.6° N. and Longitude 55.2° W. at 1900 EST on September 21 when it reported winds of 63 m. p. h.

The eye of hurricane Janet passed just south of the island of Barbados shortly after 1100 EST on the 22d. It was an immature hurricane at this time with a very small ring of hurricane winds around the 20-mile eye. The reconnaissance plane reported the wall cloud around the eye only 5 miles wide but turbulence was very severe. Maximum winds were estimated by an observer on the south side of the island at 110 to 120 m. p. h., dropping off very rapidly 20 miles out from the edge of the eye. The rapid increase in winds is illustrated by the following observations taken at Evanman, Maxwells Court, Christ Church, by Mr. H. W. Webster.

Time (AST)	*Speed* (*m. p. h.*)	*Direction*
10:45 a. m.	43	Wind mostly north to north-northeast
11:00 a. m.	58	
11:15 a. m.	62	
11:20 a. m.	64	
11:24 a. m.	66	
11:28 a. m.	70	
11:37 a. m.	72	
11:39 a. m.	82	
11:40 a. m.	90	
12:06 p. m.	50	East
Lowest barometer 29.20 inches, or 989 mb., sky brightening south, eye passing to south		
12:20 p. m.	100+ (110–120)	East-southeast

No further data are available but the storm subsided quite rapidly.

The hurricane was moving at 11 m. p. h. at this time so it can be seen the ring of hurricane winds was very narrow. The lowest pressure reported by plane in the eye just to the south of the island was 979 mb. (28.91 inches). This was the first hurricane in Barbados in 57 years. The storm passed between Grenada and Carriacou early on the 23d. Fatalities in Barbados numbered 38 and in the Grenadines 122. Property damage was in excess of $2,800,000.

During the next several days in the eastern Caribbean, Janet pursued a course generally toward the west with some actual decrease in intensity. The center was located at 3:00 p. m. on September 23 at Latitude 13.2° N. and Longitude 64.8° W. with central pressure 996 mb. (29.41 inches) and wind 92 m. p. h., radar eye 40 miles in diameter, and wind eye 20 miles N–S, 27 E–W. Turbulence was moderate, sea high, no weather bands in northern semicircle but some in the southern semicircle.

During the early hours on the 24th, according to the Navy reconnaissance plane, Janet never presented good center definition and it is not certain the center was found. Weather targets consisted of large areas of diffuse targets with no spiral relationship. All center fixes were taken on strongest, most promising targets and the plane stated the fixes were of unknown accuracy. The radar bands were so disorganized, radar coverage was not considered feasible. Late in the afternoon, one very strong spiral weather band was found although the central pressure remained about the same. The reconnaissance plane reported:

Eye centered Lat. 13.8° N. and Long. 69.9° W. at 3:02 p. m., EST, circular eye with well defined cloud and wind eye approximately 20 miles in diameter. Minimum pressure 29.38 inches, or 995 mb., maximum wind 127 m. p. h. . . . in weather band 40 miles from eye in southwest quadrant, wind shifted in weather band from 240° to 330°, band approximately 25 miles thick, section we went through showed up weakest on radar, maximum winds northwest through southwest 52 m. p. h., turbulence light to none except in weather band where it was moderate to heavy, precipitation light to none, navigation good, radar coverage not considered feasible for eye positions, however, weather band to west presents good picture.

On the 25th the eye was located at 1400 EST at Latitude 14.3° N. and Longitude 74.2° W. with a maximum wind of 98 m. p. h., central pressure 987.7 mb. (29.17 inches). The eye was described as well defined but there was evidence it was very changeable—hoop-shaped on one occasion, a figure "6" on another. One obtains the impression of a slowly but definitely intensifying storm. The reconnaissance flight on the night of September 25–26 summarizes its observations as follows:

Eye completely closed circle after 9:15 p. m., average diameter 22 miles, storm presented symmetrical pattern of intense weather bands which extended 120 miles south, 140 east, 130 north, and 170 west, high overcast throughout area, low scattered to broken stratocu with tops near 6000, thunderstorms generally oriented in spiral bands throughout area, frequent lightning.

Rapid intensification was evident.

At 0830 EST of the 26th, Lt. Comdr. Windham with crew of 8 and 2 newspapermen reported in Latitude 15.4° N. and Longitude 78.2° W. that they were about to begin penetration of the main core of the storm. No further report was ever received from this plane. Janet had become a very severe hurricane.

The Navy reconnaissance plane at 1040 EST on the 27th reported the center at Latitude 16.9° N. and Longitude 82.7° W. with lowest pressure 938 mb. (27.70 inches), and maximum winds in excess of 115 m. p. h. by a large and uncalculable amount. Janet passed over Swan Island during midday with winds estimated at 200 m. p. h. The approach of the hurricane is described by the Swan Island weather reports as received at Miami:

0710E E16 ⊕TRW 047/77/76 NNE/2 PRESSURE DOWN 8 MBS LAST 3 HRS. RAINFALL LAST 6 HRS. 0.61

0745E E10⊕1/2 RQ 041 78/76 NE/14+28/SC MVG SW SEA ROUGH

0845E E10⊕RQ 027/78/77/NNE/25+30/PRESFR CLDS SC MVG SW SEA ROUGH

0945E E10⊕1/2 RQ 000/80/77/NNE/28+34/ PRESFR SEA VERY ROUGH

1000E E16⊕R 000/80/77/N/28 PRES DOWN 4.7 MBS LAST 3 HRS.

1030E GUSTS TO 38 MPH NOW. BIG COCONUT TREE JUST WENT DOWN IN FRONT OF LIVING QUARTERS.

1045E E10⊕1/2RQ 963/81/76/NNE/48+55/PRESFR

1100E WINDS NOW 60MPH WITH GUSTS TO 75 PRESSURE 29.065 INS.

1115E? ANTENNAS GOING DOWN NOT READING YOU AT ALL. ABANDONING STATION. ALL HANDS SEEKING SHELTER IN NAVY SEISMO BUILDING. WINDS NOW ESTIMATED IN EXCESS OF 100 MPH IN GUSTS.

From memory Mr. John Leban, observer, reported:

Around 1130 EST wind estimated over 120 m. p. h.

1215 EST wind estimated over 150 m. p. h.

1250 EST wind estimated 200 m. p. h.

1310 to 1335 EST eye wind 15 to 35 knots, pressure 938 mb. (27.70 inches) (from plane).

The vivid recollections of Mr. John Leban as the hurricane passed over Swan Island will be published in *Weatherwise* at a later date.

The hurricane center reached Corozal, British Honduras, and Chetumal, Mexico, about 1 a. m., local time, September 28. It was still a very concentrated storm with winds reaching hurricane force only about 2 hours before the arrival of the eye. In Corozal the barometer read 29.34 inches at 2300 EST and 27.10 inches at 0110 EST, falling 2.24 inches in 2 hours and 10 minutes with most of the fall occurring after 2330 EST. The official minimum barometer reading in Corozal was 27.10 inches (aneroid) and another aneroid in the house of a clergyman read 27.05 inches. In Chetumal the radio operator of the Mexican Aviation Company read 920.1 mb. (27.17 inches) on the mercurial barometer some minutes before the eye arrived. The original barograph trace (fig. 6) at Chetumal was furnished by Mr. S. B. Lizama Frias, Flight Dispatch Superintendent, CIA, Mexicana de Aviation,

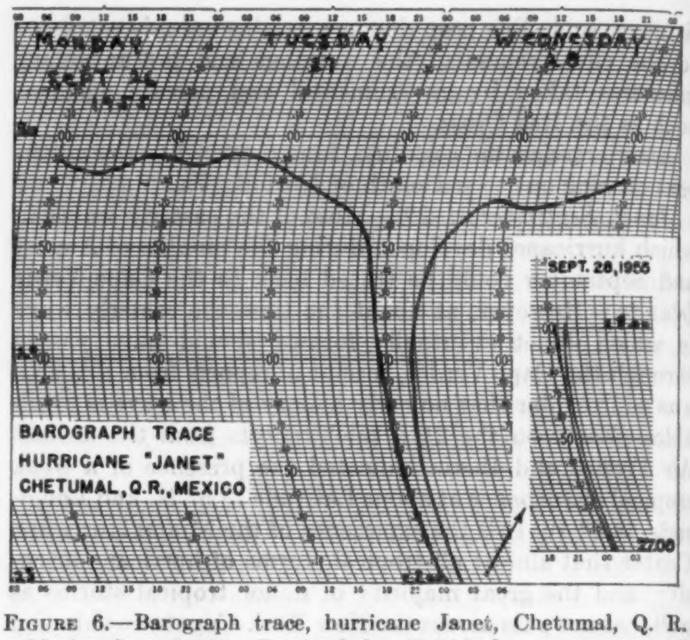


FIGURE 6.—Barograph trace, hurricane Janet, Chetumal, Q. R. Mexico, Sept. 26–28. Portion below 27.94 inches was constructed from a reliable barometer reading of 27.00 inches and the apparent diameter of the eye. (See text.)

S. A. The pen passed off the trace at 27.94 inches. A barometer reading of 27.00 inches in the eye at Chetumal was forwarded by Mr. D. N. A. Fairweather, the meteorological observer at Corozal. Corozal was in the southern edge of the eye and since the eye passed directly over Chetumal, it is believed the reading of 27.00 inches can be accepted. Therefore on the inset in figure 6 we have constructed a continuation of the trace below 28.00 inches based on this reading and the length of the period of calm at Chetumal. The lowest reliable sea level land barometer readings of record in the world are:

Lower Metacumbe Key, Fla.	September 2, 1935	26.35 inches
Basilan, P. I.	September 25, 1905	26.85 inches
Cossack, Australia	January 7, 1881	27.00 inches
Chetumal, Mexico	September 28, 1955	27.00 inches

The anemometer at the airport terminal building at Chetumal registered 152 knots or 175 m. p. h. before it collapsed. The wind continued to increase and the maximum is estimated in excess of 200 m. p. h.

In British Honduras 16 persons were killed and total damage is estimated at about $5,000,000. In Chetumal, a town of about 2,500 people, only 4 badly battered buildings were left standing. Sea water reached a height of 6½ feet some 1,600 feet inland. The area is rather well protected from the Caribbean Sea by a sizable peninsula but there was one report of a hurricane wave south of Corozal. In Chetumal approximately 120 bodies were found in and about the ruins but the sea dragged away an unknown number. Altogether in the Mexican state of Quintana Roo, the death toll is estimated at about 500 with $40,000,000 damage.

Hurricane Janet passed into the Gulf of Campeche and

moved inland between Veracruz and Nautla. The circulation aloft continued its westward movement across Mexico and a squally disturbed area developed off the west coast of Mexico under this circulation late on the first of October. Floods were already occurring in the Tampico area from the rains of Gladys and Hilda when the torrential rains of this hurricane were added. Little information is available on fatalities and damage which should be attributed to Janet in this area, but according to the Weather Bureau Office at New Orleans, the floods in the Tampico area from the tropical storms of 1955 were probably one of the greatest natural disasters ever to occur in that country.

Tropical Storm of October 10–14.—A small vortex apparently developed in an easterly wave which passed through the Cape Verde islands on October 4. It was first reported by two ships on October 10 at approximately Latitude 28.5° N. and Longitude 42.8° W. The storm recurved to the northeast on the 11th and merged with an extra-tropical storm on the 14th. The combined storm was quite severe with one ship reporting 979 mb. (28.91 inches). The lowest reported pressure in the tropical storm was 1000 mb. (29.53 inches), and highest winds were about 55 m p. h.

Katie, October 14–20.—Hurricane Katie probably developed from a wave on the intertropical convergence zone in the vicinity of Panama. The first definite evidence was a ship report from the Dutch motor vessel *Poseidon* on the morning of the 16th. A Navy reconnaissance plane the same afternoon located the center with a pressure of 984 mb (29.06 inches) and winds up to 115 m. p. h. The center crossed the coastline of Hispaniola near the border between Haiti and the Dominican Republic about midnight that night. This area is thinly populated but the small border towns of Anse-a-Pitre and Pedernales were badly damaged with highest winds estimated at 115 m. p. h. On the basis of incomplete reports, total damage is estimated at between $200,000 and $300,000 with 7 deaths.

Katie became almost completely disorganized in crossing the high mountains of Hispaniola but briefly intensified to near hurricane intensity after passing out into the Atlantic. However, it shortly reached an area containing the remains of an old cold front and again lost intensity. The vortex was probably last encountered by the SS *Amsterdam* at 0130 EST on the 20th in Latitude 37.3° N. and Longitude 56.4° W.

3. ANALYSIS OF RADAR REPORTS IN CONNIE, DIANE, AND IONE

RADAR OBSERVATIONS

A radar was installed at Hatteras, N. C., in July 1955, principally for the purpose of observing hurricanes as they passed northward either inland or out to sea on varying degrees of recurvature. A more fortunate and timely location could not have been selected since the three hurricanes which affected the United States coastline in 1955 passed within radar range of this station. Radar fixes and scope photographs for these hurricanes are to be published as a Weather Bureau *Technical Paper* to make them available for research and training purposes. In the meantime it seems appropriate to include in this annual review a brief analysis of the fixes for Connie and Diane. The fixes for Ione have already been analyzed by Jordan and Stowell [7].

All radar fixes between Latitudes 32° and 36° N. from the Hatteras station and the Navy and Air Force reconnaissance planes have been plotted for hurricanes Connie and Diane on figures 7 and 8. Hatteras radar fixes of the eye became reasonably accurate at a range of 140 nautical miles for Connie, 150 for Diane, and 160 for Ione.

Note the cyclonically curved movement of the apparent eye as indicated by aircraft radar from 0330 to 0500 EST and the two eye penetrations at 0550 and 0800 EST, and then the next eye position at 1020 EST to the south of the previous positions indicated by A at the bottom of figure 7. Compare the radar-indicated path during this period with the smoothed track of the hurricane. Was the plane following a parasitic circulation—a false eye? Note the anticyclonically curved cusps (B) from 2311 EST on the 11th to 0147 EST on the 12th and from 0147 to 0555 EST and perhaps another from 0555 to 0705 EST. Did the hurricane center actually take such a course and, if so, what is the explanation of the apparent anticyclonic curvature?

From 1100 EST on the 9th to 1700 EST on the 11th Connie moved at the rate of 5.7 m. p. h. After this time Connie began to accelerate but temporarily slowed as the center approached and crossed the North Carolina coastline. The center curved to the left just as it crossed the coast and made one or more loops, remaining quasi-stationary west and north of Morehead City for about 3 hours.

Hurricane Diane's path was the most straightforward of the three as the storm passed through eastern North Carolina. However, one loop was indicated by radar about 19 nautical miles off the coast and another possible small loop west of Wilmington (fig. 8). It will be noted that the eye remained in about the same position for 2½ hours off the coast and then was reported 31 minutes later some 33 miles to the northwest. The Hatteras observer provided us with a description of the events taking place as seen on the radar from 0317 to 0517 EST on this date—table 1. Some additional information was supplied by the Air Force plane which was in the eye at 0300 EST. It was dark, the plane was at 500 mb. and the observer reported:

Position 33.7° N., 77.4° W. [16 miles east-northeast of the interpolated Hatteras radar fix] loran position accurate within 5 miles, eye defined on radar, wall clouds on north semicircle, south semicircle open, eye well defined 45 miles in diameter, 500-mb. height 18,820 feet, alto-stratus and light rain in eye near north wall clouds, unable to make dropsonde due excessive static, lightning visible 60 miles south.

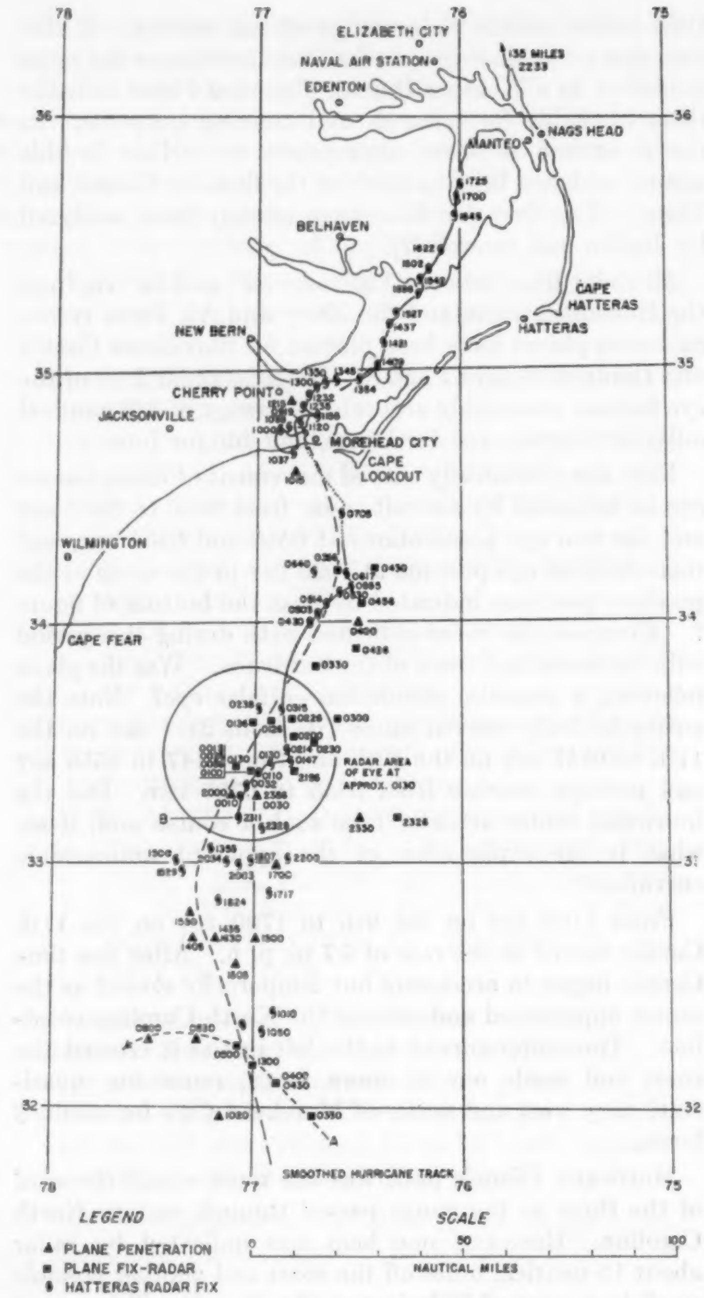


FIGURE 7.—Track and radar fixes, hurricane Connie, August 11–12, 1955.

TABLE 1.—*Observer's description of events taking place in Diane as seen on the Cape Hatteras radar, 0317–0517 EST, August 17, 1955*

Time EST	Position of eye Deg./miles	Comments
0317	229/140	Eye still difficult to define. Spiral band bounding it on N side is 100 miles in diameter.
0347	228/145	Difficult to define.
0412	226/140	Difficult to define.
0446	229/140	Appears 50 miles diameter—difficult to define.
0517	243/145	Eye appears to form into tight curl at west side of huge spiral band.

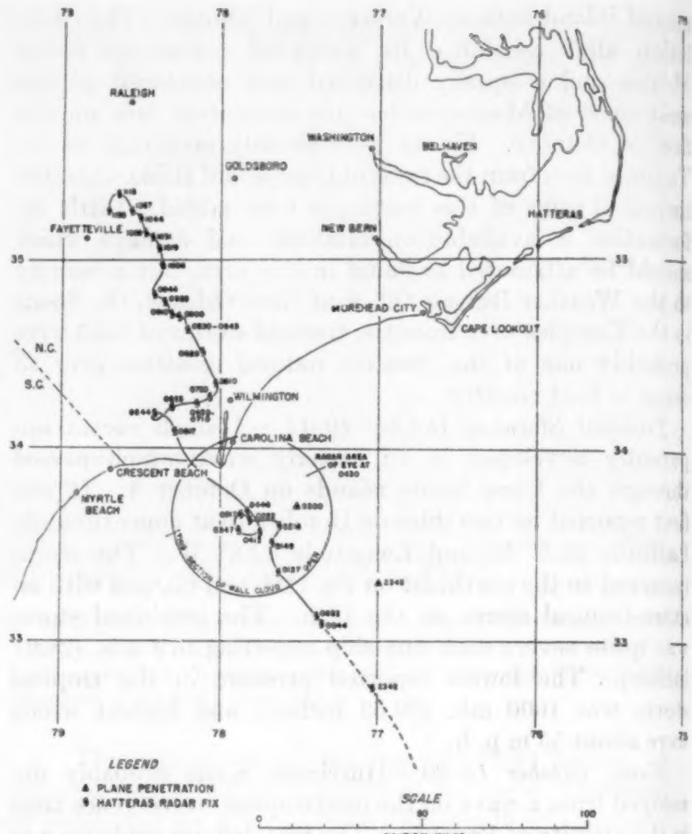


FIGURE 8.—Track and radar fixes, hurricane Diane, Aug. 16–17, 1955.

The combined plane and surface radar observations may be interpreted to mean there was a loosely defined squall eye 45 to 50 miles in diameter but the precipitation-free eye and possibly the wind eye were smaller. The squall eye did not move northwestward in straightforward fashion but the long intense spiral band moved into the old, large, and indefinite center and a new eye developed in the tight curl southwest of Wilmington. It seems definite the movement of the squall or radar eye, or whatever the radar was following, was discontinuous but it is not certain whether or not the precipitation and wind eyes moved regularly. In order to check this explanation and to see what the eye looked like from the ground, additional data were requested from Wilmington. Mr. R. L. Frost, the Meteorologist in Charge, replied as follows:

It is the opinion here that the "eye" arrived at 5 a. m. There was no marked change in the weather conditions. The sky remained overcast, the wind moderated but there was no period of calm. Evidently the hurricane was weakening and filling when it reached the coast here. It was hard to realize we were in the "eye", but from the barometric indications we must have been. The characteristic "hurricane eye weather" which we have read about in other hurricanes was missing in this storm. The lowest barometer reading was 29.13 inches at 8:15 a. m.

From the Form WBAN 10A for Wilmington, the peak gust occurred at 0249 EST. This was the intense weather

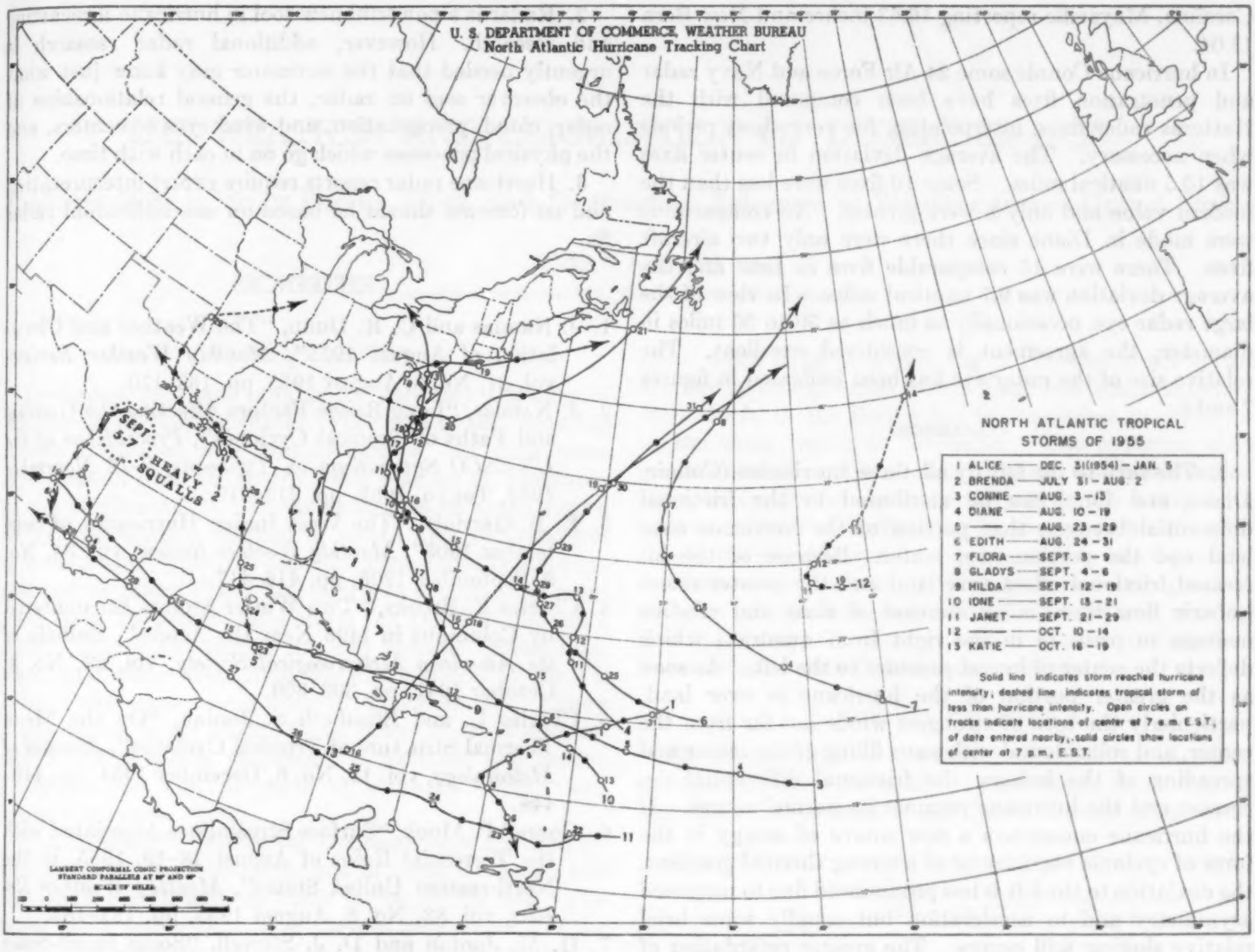


FIGURE 9.—Tracks of hurricanes and tropical storms, 1955.

band north of the eye noted on some of the radar reports. The winds and heavy rain gradually subsided until 0504 EST when "very light rain" was recorded with the remarks, "barometer steady, apparently in eye of hurricane, wind variable 10 to 25 m. p. h., breaks in overcast". The station was in the radar eye; however, intermittent light to occasionally heavy showers which were apparently not observed on the radar scopes continued until 0833 EST. At the time the radar eye was closest to Wilmington (7 miles), a heavy shower was occurring at the weather station. Highest wind after the eye passage was 45 m. p. h. with only 0.02 inches of precipitation. The wind and precipitation eye, although indefinite, would appear to have been much smaller than the radar or squall eye. By no means can the complex and disorganized eye description given by radar and ground observers at this stage of Diane be considered characteristic of hurricanes in general.

The rate of movement of Diane as the storm approached the coastline cannot be determined exactly because of the apparent discontinuous progression of the radar center but some deviation to the left and some slowing is evident while in the vicinity of and west of Wilmington. The tendency for disintegration of the eye was evidenced by the radar fixes as the center approached Raleigh, N. C. (1044–1138 EST).

The Hatteras radar observations taken in connection with Ione have been discussed by Jordan and Stowell [7]. From figures 1 and 2 in their article, the slowing and erratic movement and the turn to the left are clearly evident as Ione crossed the coastline. West of Morehead City the hurricane moved only 45 statute miles in 10 hours. There were apparently several loops and Cherry Point had 3 barometric minima, 28.42 inches at 0627, 28.43 at 0821 and 28.46 at 1030 EST. The magnitude of the rise in barometer between the minima is not known. This slow movement of Ione was probably the most important factor in the excessive rains in eastern North

Carolina, Maysville reporting 16.63 inches and New Bern 13.04.

In hurricane Connie some 24 Air Force and Navy radar and penetration fixes have been compared with the Hatteras radar fixes, interpolating for very short periods when necessary. The average deviation in center fixes was 10.5 nautical miles. Some 16 fixes were less than the median value and only 8 were greater. No comparisons were made in Diane since there were only two aircraft fixes. There were 15 comparable fixes in Ione and the average deviation was 9.7 nautical miles. In view of the large radar eye, occasionally as much as 50 to 60 miles in diameter, the agreement is considered excellent. The relative size of the radar eye has been indicated in figures 7 and 8.

CONCLUSIONS

1. The turn to the left by all three hurricanes (Connie, Diane, and Ione) can be attributed to the frictional differential between that portion of the hurricane over land and the portion over water. Because of the increased frictional effect over land and the greater cross-isobaric flow there is an increase of mass and relative increase in pressure in the right front quadrant which deflects the center of lowest pressure to the left. As soon as the greater portion of the hurricane is over land, particularly the core of strongest winds not far from the center, and coincidental with some filling of the center and spreading of the isobars, the frictional differential decreases and the hurricane resumes its normal course. If the hurricane encounters a new source of energy in the form of cyclonic vorticity or of a strong thermal gradient, the deviation to the left is less pronounced due to increased asymmetry and to acceleration but usually some brief relative slowing still occurs. The greater retardation of forward progress in connection with Ione was due to the coincidence of the frictional differential with point of recurvature.

2. Radar is a powerful new tool in hurricane forecasting and research. However, additional radar research is urgently needed that the forecaster may know just what the observer sees on radar, the general relationships of radar, cloud, precipitation, and wind eyes or centers, and the physical processes which go on in each with time.

3. Hurricane radar reports require expert interpretation and no forecast should be based on one individual radar fix.

REFERENCES

1. J. Namias and C. R. Dunn, "The Weather and Circulation of August 1955", *Monthly Weather Review*, vol. 81, No. 8, August 1955, pp. 163–170.
2. J. Namias, "Long Range Factors Affecting the Genesis and Paths of Tropical Cyclones", *Proceedings of the UNESCO Symposium on Typhoons, 9–12 November 1954*, Tokyo, 1955, pp. 213–219.
3. E. B. Garriott, "The West Indian Hurricanes of September 1906", *Monthly Weather Review*, vol. 34, No. 9, September 1906, pp. 416–417.
4. Charles F. Brooks, "Two Winter Storms Encountered by Columbus in 1493 Near the Azores", *Bulletin of the American Meteorological Society*, vol. 22, No. 8, October 1941, pp. 303–309.
5. Charles L. and Elizabeth S. Jordan, "On the Mean Thermal Structure of Tropical Cyclones", *Journal of Meteorology*, vol. 11, No. 6, December 1954, pp. 440–448.
6. Conrad P. Mook, "Surface Streamlines Associated with the Torrential Rains of August 18–19, 1955, in the Northeastern United States", *Monthly Weather Review*, vol. 83, No. 8, August 1955, pp. 181–183.
7. H. M. Jordan and D. J. Stowell, "Some Small-Scale Features of the Track of Hurricane Ione", *Monthly Weather Review*, vol. 83, No. 9, September 1955, pp. 210–215.

THE WEATHER AND CIRCULATION OF DECEMBER 1955 [1]

A Month With a Major Pacific Block and Contrasting Extremes of Weather in the United States

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1. HIGHLIGHTS

December 1955 was notable for its many extremes of weather in the United States. The cold of the preceding month continued well into December, but with some amelioration from the record levels reached in November in the Northwest [1]. In the Southwest, a sharp return to warmer weather resulted in record high temperatures in some areas. Drought conditions continued in the Central and Southern Plains States, where precipitation averaged only 10 percent of normal for October-December 1955. During the month this dry weather spread eastward, and many areas from the Plains States to the Atlantic Coast experienced their driest December. Heavy precipitation in the Pacific Coast States brought destructive floods of record proportion to northern and central California, as well as parts of southern Oregon and western Nevada.

The circulation pattern for December was featured by two major seats of blocking: one in eastern Canada and the Davis Strait, and the other in the Bering Sea. The latter block and associated southward displacement of the jet stream was intimately related to the California floods.

2. CLIMATIC BACKGROUND

The time variation of the 5-day mean zonal index at the 700-mb. level in the Western Hemisphere is shown in figure 1. After a series of violent fluctuations during October [2], a period of below normal values persisted during November and December. This long period of subnormal values of the zonal westerlies was related to the two major blocks. The first was centered in eastern Canada and the North Atlantic, where blocking was one of the outstanding features of 1955. In reviewing the weather of 1955 Klein [3] divided this block into three distinct surges of positive 700-mb. height anomaly. The most recent of these surges first appeared in northeastern Canada during the latter half of September [4]. It became well established during October in the Davis Strait, where it remained through November and December.

The second block first appeared late in October [2] in the Bering Sea. As the block in the Davis Strait weakened from a maximum height anomaly of +500 ft. in November [1] to +370 ft. in December (fig. 2), the one in the northern Pacific strengthened from a maximum height anomaly of +330 ft. in the Bering Sea in November to +530 ft. in the same region in December. The apparent shift westward of the major seat of blocking was accompanied by a sharp displacement southward of the zonal wind systems in the Pacific (fig. 3). At the same time the mid-Pacific trough of November [1] sheared into two segments, the lower latitude portion deepening and retrograding, and the middle latitude portion deepening and moving into the eastern Pacific. It was this latter trough that was associated with California's record floods.

3. THE PACIFIC BLOCK

The strong block in the northern Pacific had a dominating effect upon the weather in the Pacific Coast States, and, indeed, over most of the United States. Character-

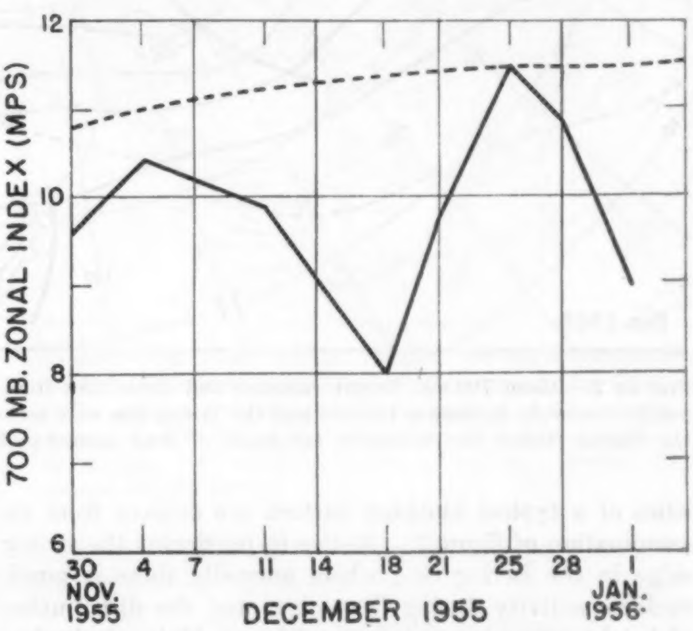

Figure 1.—Time variation of temperate-latitude zonal index (average strength of zonal westerlies in meters per second between 35° N. and 55° N.) at 700 mb. over the Northern Hemisphere from 0° westward to 180° longitude. Solid line connects 5-day mean values (plotted at middle of 5-day periods) for December. Dashed line shows variation of normal zonal index. Note the persistence of subnormal index.

[1] See Charts I-XV following p. 347 for analyzed climatological data for the month.

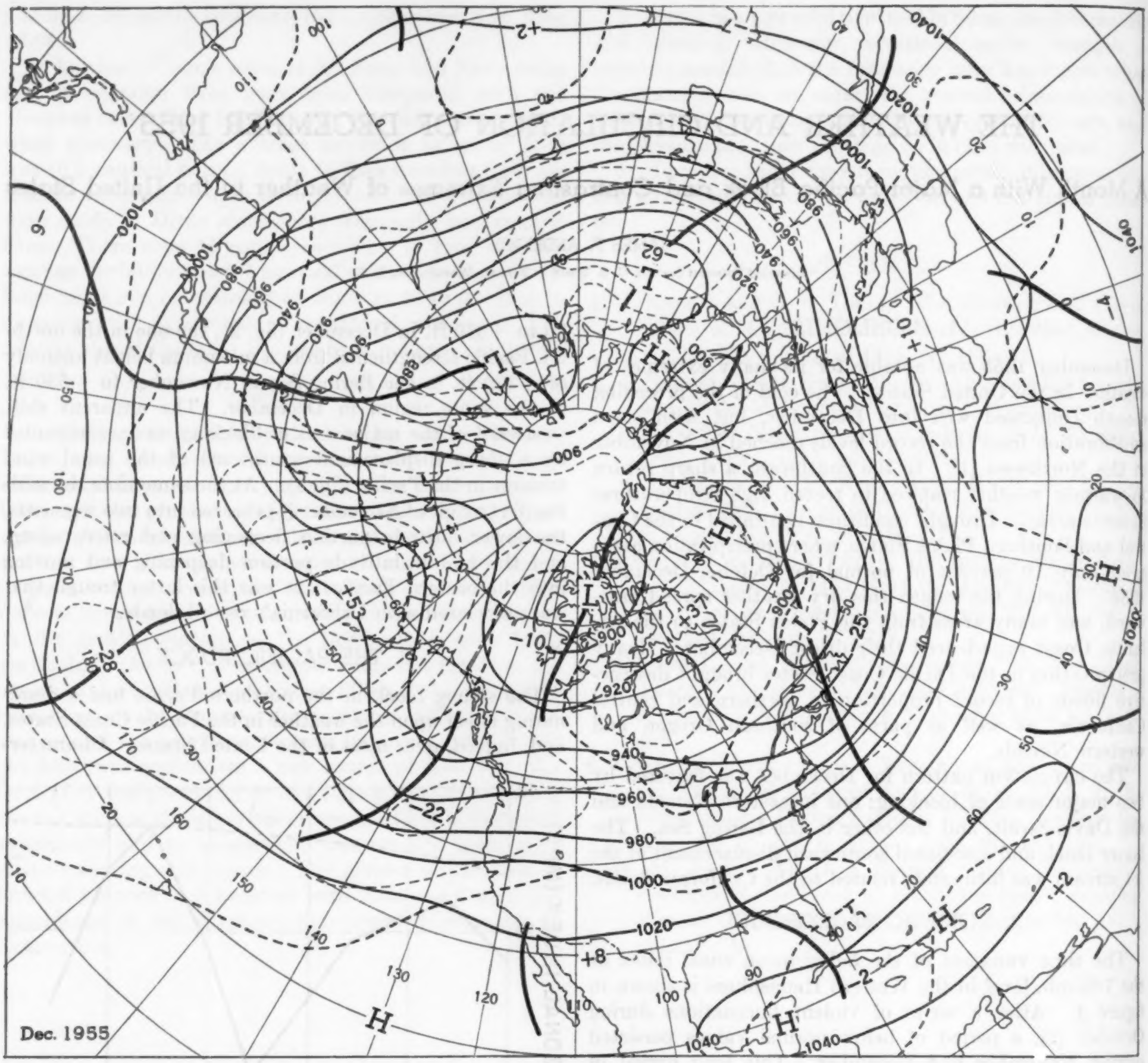

FIGURE 2.—Mean 700-mb. height contours and departures from normal (both in tens of feet) for December 1955. Large centers of positive anomaly in eastern Canada and the Bering Sea were associated with blocking ridges in those regions. The major block in the Pacific shifted the westerlies far south of their normal position.

istics of a typical blocking pattern are evident from an examination of figure 2. Notice in particular the strong ridge in the Bering Sea, where normally there is much cyclonic activity during December, and the distribution of height anomaly centers—positive in higher latitudes, and negative in lower latitudes.

This anomaly pattern was related to a marked southward displacement of the mean jet stream (fig. 4A). In the central Pacific the 700-mb. jet was as much as 13° of latitude south of normal. From its minimum latitude position the jet flowed northeastward, attaining maximum speeds off the California coast. Note the large area of above normal wind speeds in the eastern Pacific (fig. 4B). Another manifestation of the Pacific block was the vast area of subnormal wind speeds in the central Pacific, where the greatest departure observed was 14 m. p. s. A difluent area, another characteristic of blocking, was also present in the western Pacific. The major westerly jet was observed at low latitudes, while a somewhat weaker jet in the north flowed around the ridge in the Bering Sea (fig. 4A).

Sea level pressures on the monthly mean map reached an

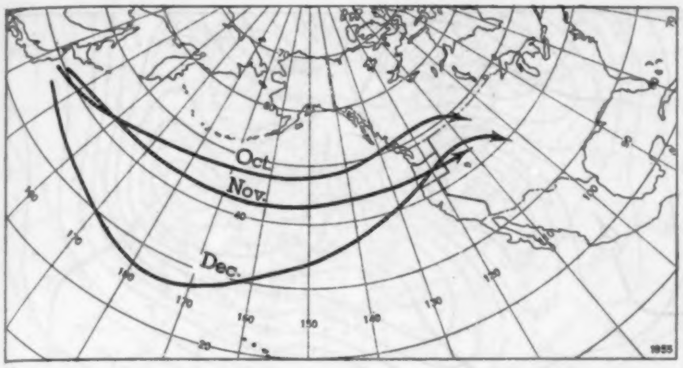

FIGURE 3.—Observed monthly positions of the mean 700-mb. jet axes for the three months, October, November, December 1955. Rapid southward displacement of the jet from November to December is notable.

extreme departure of 15 mb. above normal in the northern Pacific, while below normal pressures were observed from the western United States southwestward across the Pacific (Chart XI inset). The strong block in the Bering Sea effected a displacement of the monthly mean sea level center of action from its normal position in the western Gulf of Alaska [5] to a position about 700 miles east-southeastward (Chart XI). At the same time the major Pacific storm track was shifted far south of its normal location (Chart X).

It is also of interest to examine the evolution of the Pacific block on a weekly basis. In figure 5 are shown four observed 5-day mean 700-mb. charts, exactly one week apart, beginning with the period December 3–7 and ending with the period December 24–28. Corresponding 700-mb. height departure from normal charts are shown in figure 6. Strong westerlies (fig. 5A) and below normal heights (fig. 6A) characterized the circulation pattern of the Pacific during the first week, south of a high latitude block in the Arctic region northwest of Alaska. During the second week this block moved northward across the Arctic basin. Simultaneously a new and stronger surge of blocking made its appearance in the southwestern Gulf of Alaska, where 700-mb. heights were 610 ft. above the normal (fig. 6B). Associated with this new block was the development of a closed Low in the eastern Pacific at middle latitudes (fig. 5B). Heights continued to rise in the Bering Sea and the north-central Pacific during the third week, reaching a maximum of 10,400 ft. (fig. 5C) at 700 mb. This represents a height departure from normal of +1,400 ft. (fig. 6C), by far the greatest ever to occur in the Pacific on a 5-day mean chart during our 10-year period of record (1945–55). (It has been exceeded only once in the entire Northern Hemisphere, when an anomaly of 1,600 ft. was observed in Baffin Bay on Feb. 19–23, 1947.) Sea level pressures during this period were as much as 34 mb. above normal in the Bering Sea. This tremendous increase in pressure was accompanied by an "omega" pattern in the circulation, with marked deepening and opening northward of the eastern Pacific trough.

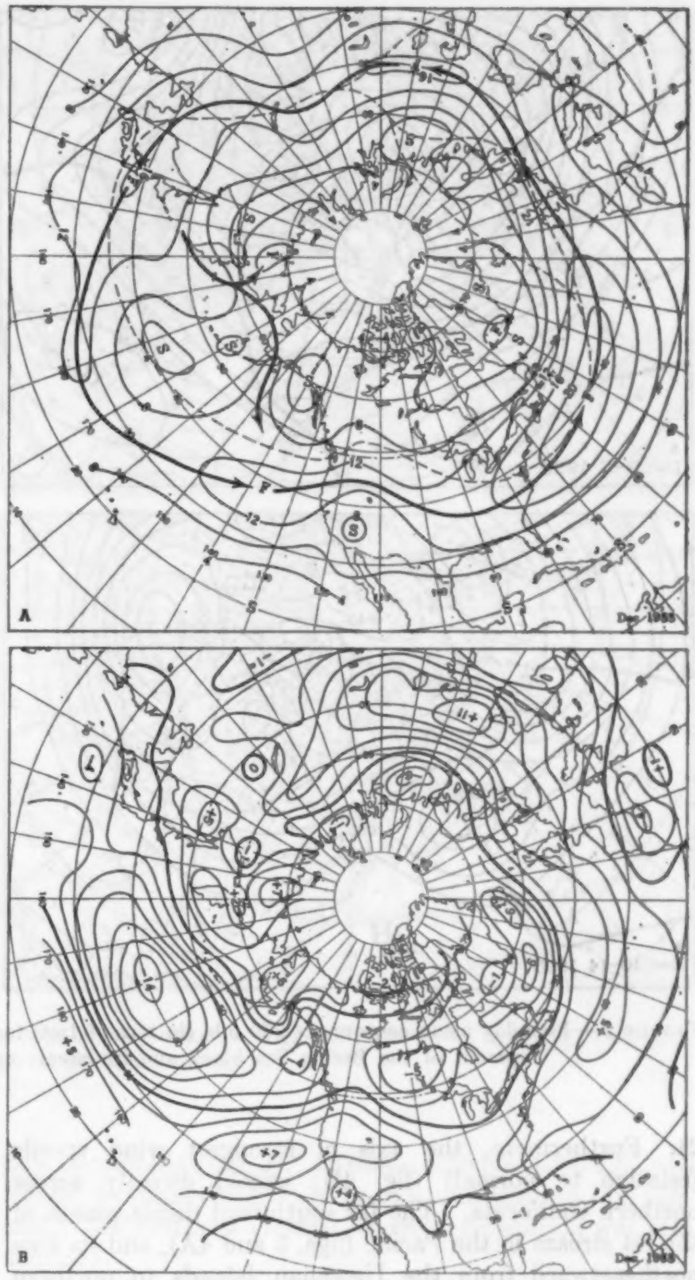

FIGURE 4.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for December 1955. Solid arrows in (A) indicate position of the primary jet axes at the 700-mb. level. Dashed lines give the normal position of the jet. "F" refers to centers of fast wind speeds; "S", to centers of light winds.

Thus was established the circulation pattern associated directly with the California floods.

4. THE CALIFORNIA FLOODS

It is well known that precipitation on the Pacific Coast is dependent largely upon the strength of the flow normal to the mountain barrier. It is not surprising then, to find stronger than normal southwesterly flow from California to Washington on the monthly mean 700-mb. chart (fig.

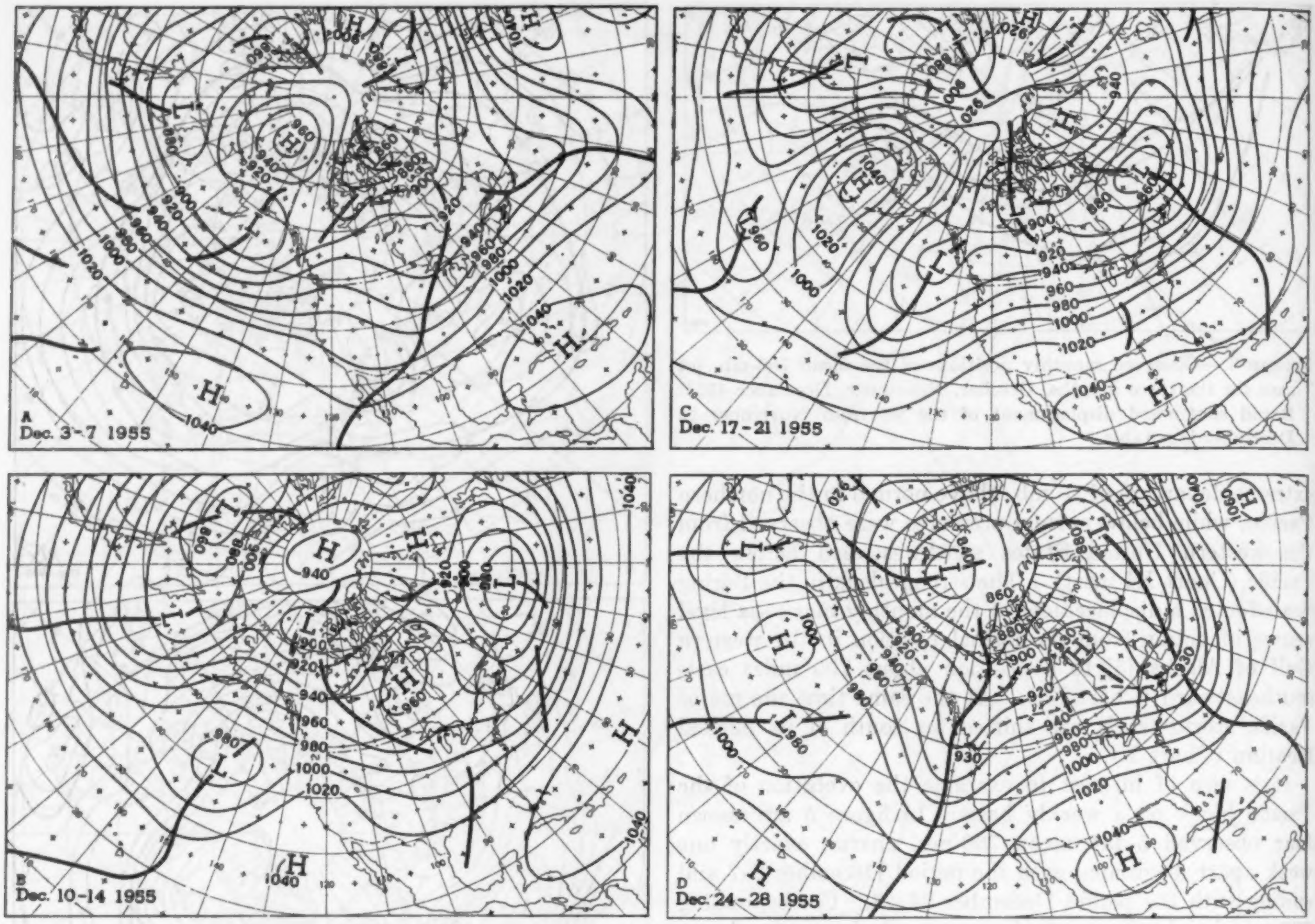

Figure 5.—Five-day mean contours at 700 mb. (in tens of feet) for four selected periods in December 1955 one week apart. Development of the Bering Sea block and its effects upon the circulation pattern downstream are striking.

2). Furthermore, the axis of strongest wind speeds (relative to normal) (fig. 4B) passed directly across northern California. The far southward displacement of the jet stream in the Pacific (figs. 3 and 4A), and its flow northeastward from the Hawaiian Islands to northern California, insured that air masses following this trajectory would be well saturated with moisture by the time they reached the Pacific Coast. Indeed, the southward displacement and long fetch of the jet stream in the Pacific was even greater during the onset of the heaviest rains (fig. 5C).

Frequent baroclinic wave developments in the mean trough in the eastern Pacific brought northern and central California a combination of warm, moisture-laden air, high winds, and heavy rain. This resulted in rapid melting of mountain snows and caused many rivers to rise to record levels. There was also some flooding in portions of Oregon and western Nevada. Table 1 lists representative stations in the heavy rain belt, along with their precipitation totals for the period December 16–26 inclusive, total monthly precipitation, and comparative data.

Table 1.—*Precipitation (inches) for the period December 16–26, 1955 with monthly totals for December 1955 and comparative data*

Station	Total precipitation Dec. 16–26	Monthly total	Normal	Percentage of monthly total to normal
Eugene, Oreg.	14.56	[a] 19.49	6.00	325
Roseburg, Oreg.	11.66	[a] 15.74	4.93	320
Medford, Oreg.	6.55	[a] 8.77	3.13	280
Mt. Shasta, Calif.	14.86	[a] 17.48	5.39	324
Eureka, Calif.	7.81	11.63	6.09	191
Red Bluff, Calif.	4.10	7.71	4.23	182
Blue Canyon, Calif.	35.22	[b] 45.12	8.75	515
Reno, Nev.	5.07	[a] 5.25	0.94	559
Sacramento, Calif.	9.94	[c] 12.20	3.19	382
San Francisco, Calif.	6.97	[d] 11.47	4.07	282
Fresno, Calif.	4.41	[a] 6.73	1.63	413
Bishop, Calif.	3.79	4.02	0.89	452

[a] New December record.
[b] Record for any month.
[c] Greatest December total since 1867.
[d] Greatest December total since 1889.

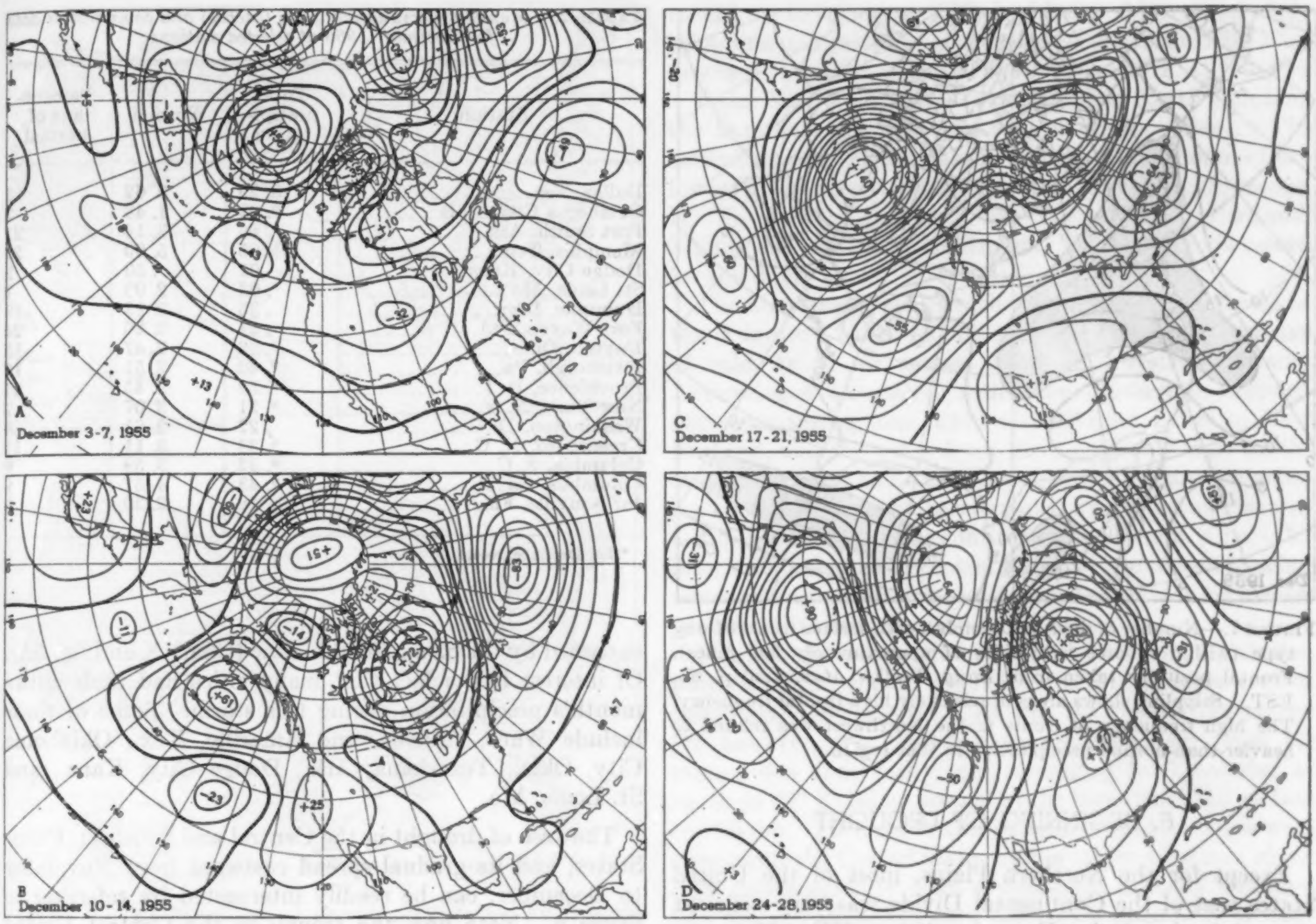

FIGURE 6.—Five-day mean 700-mb. height departures from normal (in tens of feet) accompanying the patterns in figure 5. Outstanding feature is the 1400-ft. center of positive anomaly (C).

Note that many stations received three to five times their normal amounts for the month. The greatest monthly total was 45.12 inches at Blue Canyon, the largest amount of precipitation for any month of record at that station. The continued advance of the mean trough to the Pacific Coast brought an end to the heavy rains after the 26th, although most localities reported light amounts thereafter. In general, the heaviest rains fell just south of the jet stream as it crossed Oregon. (For further meteorological details on the floods see the article by Cole and Scanlon elsewhere in this issue.)

5. PRECIPITATION IN OTHER AREAS OF THE WEST

It is somewhat ironic, although not unusual, that while central and northern California were receiving record rains, the southern portion of the State was very deficient in precipitation. Los Angeles and San Diego received but 36 and 13 percent, respectively, of their normal amounts for the month (Chart III-B). This deficiency was related to above normal 700-mb. heights and to weak anomalous flow components (fig. 2). Cyclonic activity (Chart X) and frontal frequency (fig. 7) were at a minimum in this area and in the southern Plateau, where precipitation was also deficient.

The heavy precipitation of the north Pacific States streaked east of the mean ridge (fig. 2), as far as the Northern Plains States. Frequent over-running of cold Canadian air by warmer moist Pacific air resulted in record amounts in some instances. Sheridan, Wyo., reported its wettest December of record, both in total precipitation and snowfall. At Lander, Wyo., 16 inches of snow fell on the 22d and 23d. It is apparent from Chart X that most of the storms in the northwestern United States followed a path just north of the jet axis, and were steered eastward by the upper level flow. In the area of heaviest precipitation, surface fronts were present as much as two-thirds of the time during the month (fig. 7). Although not strictly applicable to the Far West, the schematic precipitation model prepared by Klein [6] bears a strong resemblance to the observed precipitation pattern in this area.

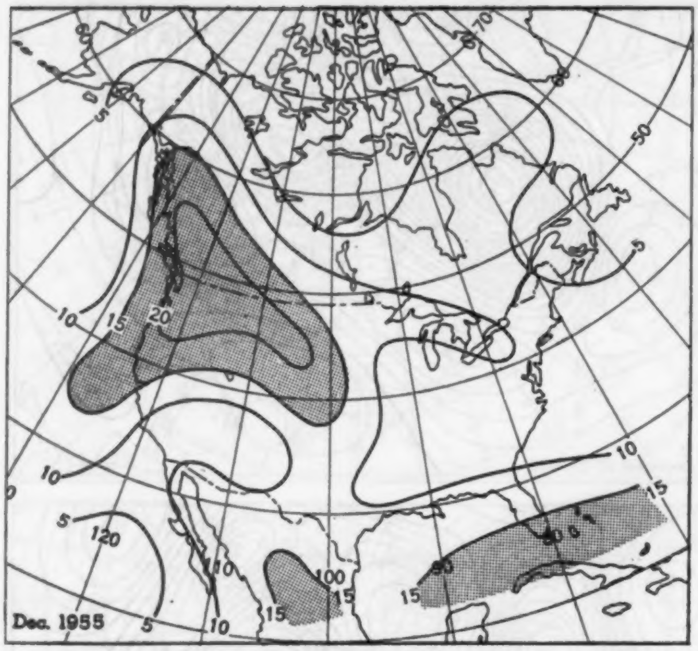

FIGURE 7.—Number of days in December with surface fronts of any type (within squares with sides of approximately 500 miles). Frontal positions taken from *Daily Weather Map*, 1:30 p. m., EST. Stippling shows areas of relatively high frontal frequency. The high frequency of fronts in the Northwest was related to heavier-than-normal precipitation in that region.

6. BEGINNING OF DROUGHT

Except for the Northern Plains, most of the United States east of the Continental Divide was very deficient in precipitation during December (Chart III). This continued a trend begun in October. Quoting from the *Weekly Weather and Crop Bulletin* for the week ending January 9, 1956 [7].

In contrast to the recent heavy precipitation and wet soils in the middle and north Pacific areas, a serious soil moisture deficiency persists in the middle and southern portions of the Great Plains and far southwestern Border districts and to a slightly less degree in many middle and southern areas east of the Mississippi River. A large portion of the country, extending from the Mexican Border northeastward to the middle Atlantic Coast, received less than 10 percent of the usual precipitation during the last 5 weeks, as presented by [figure 8A]. [Figure 8B] shows the persistency of the drought, particularly in the Great Plains where the total precipitation for the last 13 weeks was less than 25 percent of the normal from Iowa and Missouri to the Mexican Border, with less than 10 percent in western Missouri, southern Kansas, most of Oklahoma, northwestern Texas, and most of New Mexico, Arizona, and extreme southern California.

Many cities from Texas to New England, established a record or near record for December for the least amount of precipitation. A representative list of such cities, along with observed precipitation amounts, the normal, and percentage of normal, is shown in table 2.

Most of the precipitation in the Great Plains fell early in the month. It was related to a single storm that developed in the southern Rockies and was steered northeastward by the mean 700-mb. flow (Chart X and fig. 5A). Of interest is the fact that many cities had their entire month's precipitation during this storm. Some of these include Waco, Abilene, and Amarillo, Tex., Oklahoma City, Okla., Texarkana, Ark., Dodge City, Kans., and St. Louis, Mo.

TABLE 2.—*Monthly precipitation totals (inches) and comparative data for December 1955 at selected stations*

Station	Total precipitation	Normal	Percentage of normal
Dallas, Tex.	0.29	2.62	11
Oklahoma City, Okla.	*.03	1.48	2
Fort Smith, Ark.	.66	3.14	21
Memphis, Tenn.	1.05	5.09	21
Dodge City, Kans.	.01	.50	2
St. Louis, Mo.	*.03	2.09	1
Dubuque, Iowa	.36	2.13	17
Fort Wayne, Ind.	.54	2.26	24
Dayton, Ohio	*.36	2.47	15
Pittsburgh, Pa.	*.40	2.51	16
Providence, R. I.	*.58	2.45	24
New York, N. Y.	*.21	3.07	7
Washington, D. C.	.22	2.61	8
Greensboro, N. C.	*.33	3.11	11
Columbia, S. C.	*.32	3.59	9
Columbus, Ga.	*.43	4.57	9
Jacksonville, Fla.	.18	2.39	8

*New December record

The area of drought in the Central and Southern Plains States, and its gradual spread eastward from November to December, can be readily interpreted by referring to figure 5. Note how the trough in the Central United States was gradually replaced by a well-developed ridge by month's end. This trend toward anticyclonic flow is also apparent in figure 6, where the 700-mb. height anomaly changed from −320 ft. to +310 ft. as the ridge developed. The monthly mean upper level patterns for December (fig. 2 and Charts XII to XV) show that the United States, from the Rockies to the Atlantic Coast, was under the influence of winds from the west and northwest. This flow pattern effectively prevented the influx of moisture from the Gulf of Mexico. The relative persistence of this pattern from week to week (fig. 5) was also a condition associated with drought [8]. Stronger than normal westerly winds blowing over the Rocky Mountains (fig. 4B) produced a strong "rain-shadow" effect in the Central and Southern Great Plains.

Cyclonic activity, developing in the long-wave trough off the Atlantic Coast, was too far east to affect the United States (Chart X). In this respect note that only one storm was tracked through an area extending from the middle Mississippi Valley to Florida during the entire month. That storm developed in extreme northwest Florida and deepened rapidly as it moved into the mean trough. The almost complete absence of cyclonic activity in this region is related also to a minimum frequency of fronts (fig. 7). The presence of a weak trough in the east

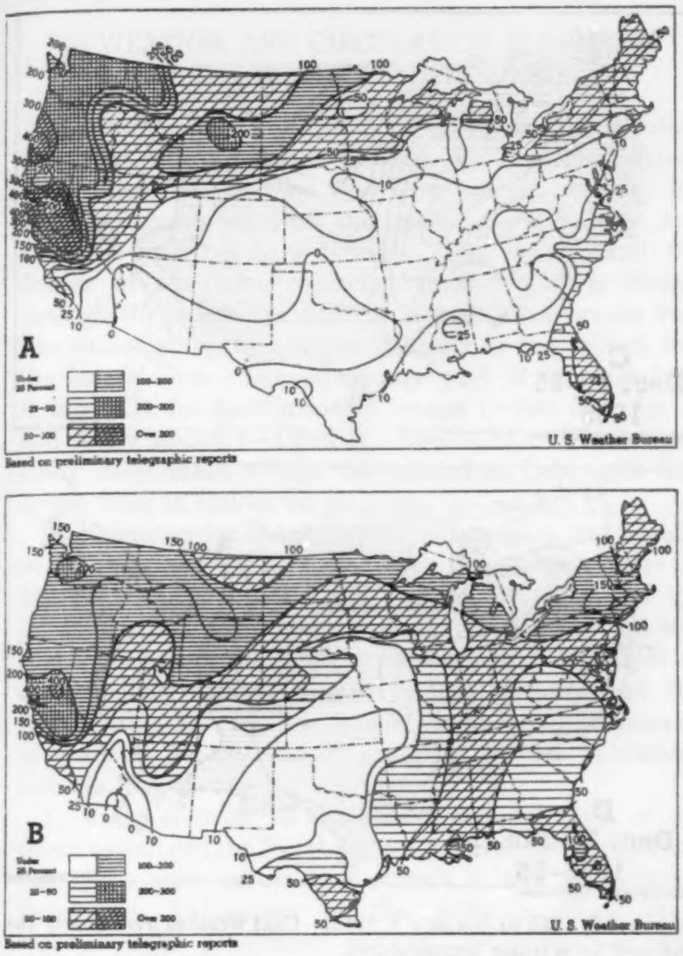

FIGURE 8.—(A) Percentage of normal precipitation for 5 weeks ending midnight, l. s. t., January 8, 1956. Note large excesses in northern and central California, and a marked deficiency from the Far Southwest to the middle Atlantic States. (B) Percentage of normal precipitation for 13 weeks ending midnight, l. s. t., January 8, 1956. Persistence of drought conditions is apparent in the central and southern Plains States. (From *Weekly Weather and Crop Bulletin, National Summary,* vol. XLIII, No. 2, January 9, 1956.)

central Gulf States and eastern Gulf of Mexico (fig. 2) was associated with moderate amounts of precipitation in the Gulf Coastal Plain.

7. TEMPERATURE AND CIRCULATION

December's temperature anomaly pattern (Chart I–B) was characterized by a sharp gradient from the Northern Plains to the Colorado Plateau. In this connection it is interesting to note how the cold Canadian air was contained north of the axis of the mean jet from the Pacific Northwest to the Central Plains (fig. 4A). Temperatures remained well below normal from the Far Northwest to the Atlantic Coast (Chart I-B). Portions of the Dakotas experienced temperatures of 10° F. below normal for December, whereas in November they were as much as 18° F. below normal. Combined records for the two months show that this was the coldest November—December on record at Helena and Billings, Mont. Many new daily minimum temperature records were established in Minnesota on the 19th, with an extreme of −45° F. at Bemidji.

From New York and New England to North Carolina, the month ranks with the coldest of Decembers. The coldest day in the Northeast was the 21st. Some of the lowest temperatures reported at this time were: Syracuse, N. Y., −20° F.; Albany, N. Y., −17° F.; Portland, Maine, −14° F.; and Burlington, Vt., −22° F. (a record for the day).

The abnormally cold weather from the Plains States to the Atlantic Coast was the result of frequent outbreaks of cold Arctic air masses from northwestern Canada. Anticyclones associated with these outbreaks followed two main tracks: one north of the Great Lakes to New England, and the other from the Northern Plains southeastward (Chart IX). High pressure on the monthly mean sea level chart was quite extensive, averaging as much as 6 mb. above normal in south-central Canada (Chart XI inset). Northern and central Florida experienced freezing temperatures on several occasions as cold Polar air masses penetrated to lower latitudes.

It is not apparent, perhaps, why the 700-mb. circulation pattern (fig. 2) should result in such an extensive area of subnormal temperatures. As was the case in November [1], however, the Canadian source region for polar air masses was abnormally cold, averaging for December as much as 16° F. below normal in the layer from the surface to 700 mb. Portions of this extremely cold air mass were swept into the United States by the upper-air winds which were predominantly from a west-northwesterly direction (fig. 2). An abundant snow cover over most of New England westward to the Lakes Region and the Northern Plains States as far as western Washington, also helped keep temperatures below normal (Chart V).

The western portion of the nation, from Texas to Oregon, experienced a return to above normal temperatures from the subnormal levels of November. Related to this warming was the development of a mean long-wave ridge over the Far West (fig. 2). This ridge, although of little amplitude, was associated with an anomalous height change of +100 ft. from November to December.

The warming trend is shown more dramatically by reference to figure 9. Note that the coldest weather in the Plains States occurred early in the month, with temperatures as much as 21° F. below normal for the week ending December 11 (fig. 9A). Northwesterly flow aloft (fig. 5A and B) and below normal 700-mb. heights (fig. 6A and B) were associated with this frigid weather. Rapid development and eastward motion of the eastern Pacific trough, along with building of the upper-level ridge over the Rockies (fig. 5C), resulted in marked warming in the West after mid-month. This was associated with backing of the upper-level winds from northwest to southwest (fig. 5B, C, D). Note also the increase in 700-mb. heights in the West, and the onset of southwesterly anomalous flow (fig. 6). At Salt Lake City, Utah, where tempera-

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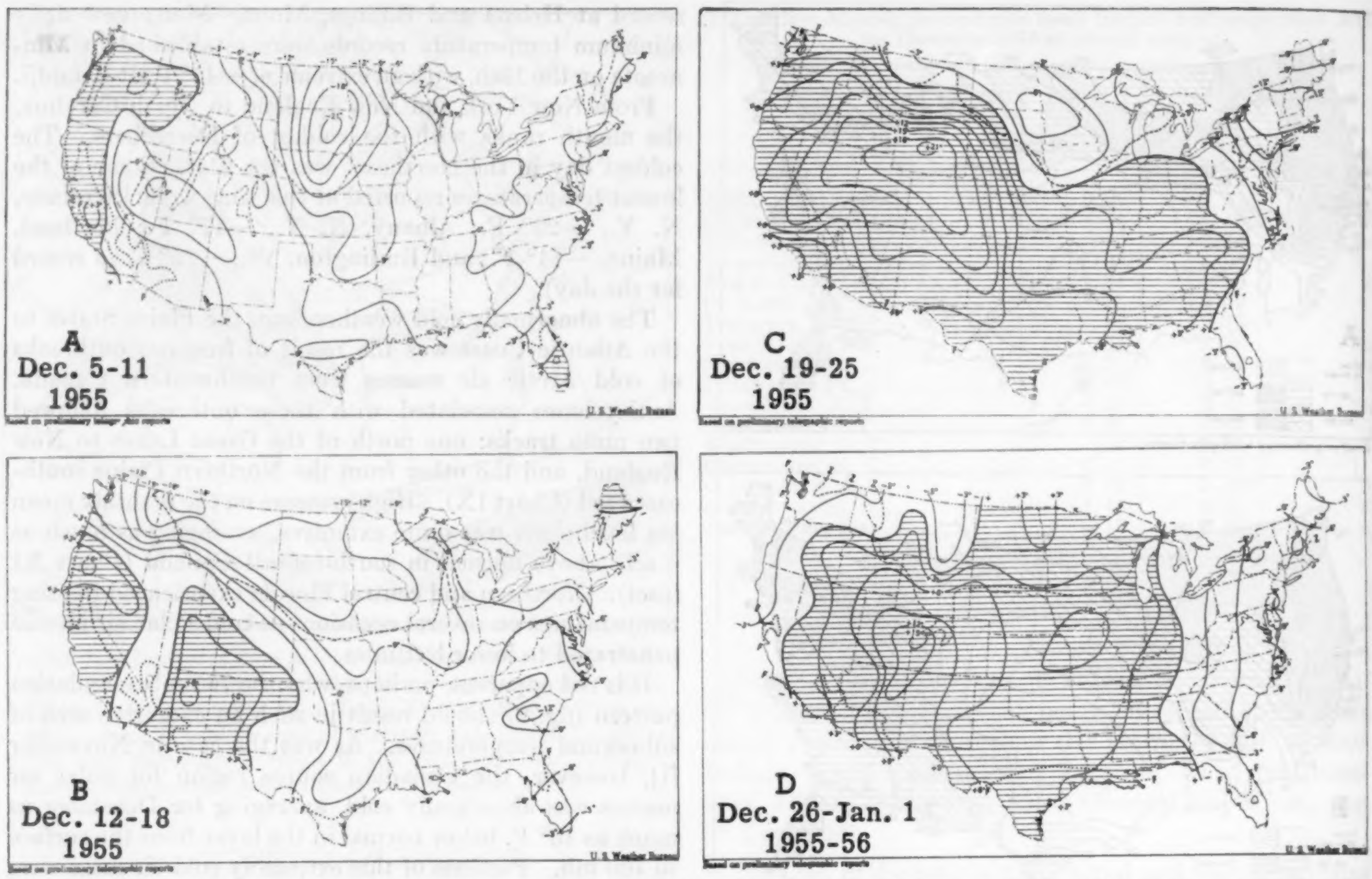

FIGURE 9.—Weekly departure of average temperature from normal, December 5, 1955 to January 1, 1956. Cold weather over nearly the entire United States was gradually replaced by warmer temperatures.

tures averaged below normal during the first half of the month, the latter half was so mild that the average for the month made this December the 2d warmest on record. Moreover, a minimum temperature of 52° F. on the 23d was a record high minimum for any winter month.

Strong and persistent southwest winds, surface and aloft, flooded the West with warm Pacific air. This, coupled with marked foehn warming, resulted in many stations in Wyoming and Colorado reporting daily average temperatures of 30° F. above normal. For the week ending December 25, Wyoming had temperatures averaging as much as 21° F. above normal (fig. 9C). At the time of greatest warming, a deep low pressure system, passing eastward through Montana on the 22–23d, brought Helena its lowest sea level pressure (982 mb.) in 76 Decembers. Very high winds were associated with this storm—Sheridan and Lander, Wyo., reporting sustained winds of 63 m. p. h. and 66 m. p. h. respectively, and the latter city a peak gust of 78 m. p. h. As a result of these strong westerly winds and a pronounced foehn effect, many cities in the Central and Southern Plains States broke all-time December heat records. For comparison some of these are listed in table 3. In addition, many new records (too numerous to mention) of daily maximum temperatures were established at cities throughout the Rocky Mountain States, and as far east as the Tennessee Valley. As this mild weather was swept eastward, nearly all areas from the Mississippi Valley to the Atlantic Coast reported their warmest days of the month on the 24th or 25th. Christmas Day was the warmest ever recorded in southern Virginia, eastern Tennessee, the Carolinas, and northern Georgia.

TABLE 3.—*New absolute maximum temperatures (°F.) observed in December 1955*

Station	Maximum temperature	Date
Colorado Springs, Colo	77	23
Dodge City, Kans	86	24
Wichita, Kans	83	24
Oklahoma City, Okla	86	24
Abilene, Tex	*89	24
Dallas, Tex	89	24
Waco, Tex	91	24
Little Rock, Ark	*80	24
Shreveport, La	84	24

*Equalled previous record.

8. WEATHER AND CIRCULATION ELSEWHERE IN THE NORTHERN HEMISPHERE

Two major long-wave troughs appear on the monthly mean 700-mb. circulation pattern (fig. 2) in the Eastern Hemisphere. Both were near their normal positions [5]. The first was located off the eastern Asiatic Coast and extended into northern Siberia. The second, and the deeper of the two, extended from Northern Russia through the Black Sea and the eastern Mediterrean Sea. The extreme negative height anomaly in this trough was the largest ever observed in any part of the Northern Hemisphere for both monthly means (−620 feet, fig. 2) and 5-day means (−1,090 ft., Dec. 7–11). This abnormally deep mean trough was related to Lebanon's first severe flood in history on the 18th.

The circumpolar nature of the jet stream is not usually so well defined as it was during December. Note in figure 4A the sinusoidal and continuous nature of the jet axis. Over the Atlantic Ocean this 700-mb. jet was slightly south of its normal position, a direct effect of the blocking operating over eastern Canada and the North Atlantic. In this connection note the persistence of positive 700-mb. height anomaly centers in eastern Canada (fig. 6).

In sharp contrast to the almost complete lack of cyclonic activity in the Northeastern Atlantic during November, there were many deep storms in this area during December. Relaxation of the Atlantic block from November to December allowed the mean sea level center of action (Icelandic Low) to return to close to its normal position (Chart XI and [5]). At the same time, the westerlies increased in strength and were above normal in middle latitudes from the eastern United States across the Atlantic to Great Britain (fig. 4B). On the 28th a severe storm with sea level pressure of 950 mb. passed to the north of Scotland, bringing gales with gusts to 70 m. p. h. to the British Isles.

Continued presence of a strong ridge in the Bering Sea, along with strong northerly anomalous flow (fig. 2), brought colder than normal weather to all but southwestern Alaska. At Juneau, on the southeast coast, the average monthly temperature was 9.5° F. below normal. Northway, in the interior of eastern Alaska, registered a minimum temperature of −57° F. on a day when the maximum temperature was only −44° F. Many Alaskan snowfall records for the month were broken, particularly in the southern portion. At the end of the month Anchorage had a record snow depth of 47 inches on the ground, due primarily to a heavy snowstorm from the 27th to the 29th.

A deep low-latitude trough, with 700-mb. heights 280 ft. below normal, was located in the Pacific near Midway Island (fig. 2). One rather severe Kona storm, associated with this mean trough, brought heavy rains and high winds to the Hawaiian Islands from the 19th to the 22d. This occurred at a time when the Bering Sea block reached its greatest strength, and southwesterly anomalous flow over the Islands was strongest (figs. 5C and 6C).

9. ODDITIES IN THE WEATHER

December's weather was not without its vagaries. For instance, in Akron, Ohio, which experienced its driest December in 68 years of record, precipitation (trace or more) fell on all but three days! This unusual circumstance was the result of frequent light snow flurries, with amounts too small to measure. And in Minneapolis, Minn., lightning and thunder were observed during a light snowfall, the first such occurrence of its kind in December since records began in 1890.

REFERENCES

1. C. M. Woffinden, "The Weather and Circulation of November 1955—A Month With Pronounced Blocking and Extreme Cold," *Monthly Weather Review*, vol. 83, No. 11, Nov. 1955, pp. 272–278.
2. C. R. Dunn, "The Weather and Circulation of October 1955—A Month With a Double Index Cycle," *Monthly Weather Review*, vol. 83, No. 10, Oct. 1955, pp. 232–237
3. W. H. Klein, "The Circulation and Weather of 1955," *Weatherwise*, vol. 9, No. 1, Feb. 1956.
4. A. F. Krueger, "The Weather and Circulation of September 1955," *Monthly Weather Review*, vol. 83, No. 9, Sept. 1955, pp. 206–209.
5. U. S. Weather Bureau, "Normal Weather Charts for the Northern Hemisphere," *Technical Paper* No. 21, Washington, D. C., 1952, 74 pp.
6. W. H. Klein, "An Objective Method of Forecasting Five-Day Precipitation for the Tennessee Valley," *Research Paper* No. 29, U. S. Weather Bureau, Apr. 1949, 60 pp.
7. U. S. Weather Bureau, *Weekly Weather and Crop Bulletin, National Summary*, vol. XLIII, No. 2, Jan. 9, 1956.
8. J. Namias, "Some Meteorological Aspects of Drought—With Special Reference to the Summers of 1952–54 over the United States," *Monthly Weather Review*, vol. 83, No. 9, Sept. 1955, pp. 199–205.

FLOOD-PRODUCING RAINS IN NORTHERN AND CENTRAL CALIFORNIA, DECEMBER 16–26, 1955

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1. INTRODUCTION

Northern and central California was the scene of unusually heavy rains and destructive flooding during the period December 16–26, 1955. Rainfall amounts exceeded many existing records and flood conditions were described as the worst in the history of northern California. Preceded by periods of moderate to heavy rains during the first half of the month, the record-breaking deluge fell on rain-soaked soil and drained into already rain-swollen streams. Rivers overflowed their banks and went on to cause the costliest flood on record for the area. News reports listed 66 deaths as a result of the floods, and preliminary property damage estimates exceeded $150,000,000. Thousands of people were forced to evacuate their homes, five small towns were reported "wiped out," and transportation was disrupted by high water, slides, and bridge washouts.

December climatological data immediately available emphasized the intensity of this storm period with a number of new rainfall records. Oakland and Blue Canyon reported December 1955 as the wettest month on record. Fresno, Mt. Shasta, and Medford reported the wettest December on record. Stations with longer histories found comparisons in the last century: San Francisco reported the wettest December since 1889 and Sacramento since 1867.

The occurrence of moderate to heavy rains in this part of the country is generally regarded as a normal wintertime feature and has been described many times in literature. Several investigators, Vernon [1], Martin and Hawkins [2], and Hughes and Roe [3], to name a few, have found that the rain mechanism for northern and central California is largely due to topography, a strong southwesterly flow, and an ample supply of moisture. Since the rainfall in this case was unprecedented, it is surmised that the interaction of these factors was excessive both in time and amount. Therefore, this article is primarily concerned with a discussion of some of the more pertinent synoptic and climatological aspects of the heavy rains and ensuing floods. Included in the discussion are comments on the persistency of the synoptic situation, distribution and intensity of Low centers passing over northern California, relationship of the jet stream, strength of vertical velocities, temperature features, and the importance of strong low-level flow. Furthermore, rainfall amounts are compared with past records and related to both gradient and topography. Most of the synoptic charts used in this article were reproduced from the operational charts of the National Weather Analysis Center. Also, it should be emphasized that much of the rain and flood data were based on preliminary reports and subject to future revision. More complete data will be printed in *Climatological Data, National Summary* for December 1955.

2. ANTECEDENT CONDITIONS

For the first two weeks of December, the 500-mb. flow pattern over northern California was predominantly west to northwest which permitted several short-wave systems to pass onto the Pacific coast. Specifically, one sea level Low passed onshore just north of Crescent City on December 1, and six occluded fronts passed over northern and central California during the 2-week period. Other Low centers entered either the coast of Washington or British Columbia. These minor storms produced moderate to occasionally heavy precipitation along the Pacific coast area north of Monterey Bay. Many stations received more than half their normal December rainfall by the 14th (table 2). At least two stations, Fresno and Oakland, received more than their December normal by mid-month, and several other stations received nearly as much. These antecedent rains soaked the soil, filled the streams, and prepared the scene for destructive flooding.

3. SYNOPTIC FEATURES DECEMBER 16–26

Around the middle of December, the 500-mb. flow pattern exhibited a change in regime. A flat persistent ridge along the Pacific coast moved inland, and the flow over northern and central California became southwesterly. At the same time, a blocking High cell in the Kodiak-Bering Sea area began increasing in intensity, and a pronounced trough was established in the eastern Pacific Ocean. (See article by Andrews [4] on the mean circulation pattern.) In general, this trough extended from the Alaska Panhandle to Hawaii. 500-mb. Low centers appeared in this trough, 600 to 700 miles west of

the Seattle area, on December 15, 18, and 24. These Lows moved slowly eastward or northeastward and were absorbed within two or three days into the circulation of a large Low pressure system centered over northern Canada. Moving eastward with the Low of the 24th, the persistent trough passed over the Pacific coast on December 27.

At the surface, the first Low of the series moved over the Oregon-Washington coastline on the 16th and filled. It was accompanied by a weak trough over northern California that caused some light precipitation on the 15th and slightly larger amounts on the 16th. Rainfall amounts with this first Low were insignificant when compared with amounts that fell later.

On December 17, the rainfall intensity became a little heavier. This rain occurred in advance of an occluding Low center located about 1,600 miles west of San Francisco on December 16. Reaching the Pacific coast by the 18th, this Low and accompanying fronts (fig. 1a) was immediately followed by a wave of considerable vigor on December 19. The surface and 500-mb. features are shown in figure 2a. The strong pressure gradient associated with this wave created high winds at the surface and upper levels. Forty to sixty knot winds were reported by stations along the northern coast of California and by ships 100 to 200 miles off shore. At Oakland, the 850-mb. winds reached a maximum speed of 65 knots on the 19th. The presence of these strong winds plus a modest influx of moist tropical air produced exceedingly heavy rains over northern California. Somewhat smaller amounts fell over central California as the accompanying frontal system pushed southeastward (fig. 1a) and frontalized near Fresno.

Stations in an area from Crescent City to a point south of Point Arena and thence inland to Sacramento and Mt. Shasta reported more precipitation for the 4-day period December 17–20 than they did for the next 4 days, the period of heaviest rainfall for the remainder of California northwest of Bakersfield. A 24-hour total of 3.27 inches between the 18th and 19th at the Sacramento City Office set a new December record.

The second surge of heavy rain began on December 21. Late on this day, an increase of warm moist air and strong southwest winds over northern California were associated with a fairly intense occlusion crossing the Oregon-Washington coast (fig. 1b). In addition to this frontal system, another occlusion was located about 900 miles west of California and a developing wave in the Johnson Island area. By December 22, the second occluded front had passed over northern California (fig. 2b); and the wave was racing toward the Pacific coast. Both the 500-mb. contours and the surface isobars indicated a long tropical fetch, a very important factor in the California rain mechanism. The 18,800-ft. 500 mb. contour extended from the latitude of the Hawaiian Islands eastward to Oakland and Sacramento. North of the Hawaiian Islands, the confluence of warm and cold air created a very strong jet stream from the south Pacific Ocean to the coast

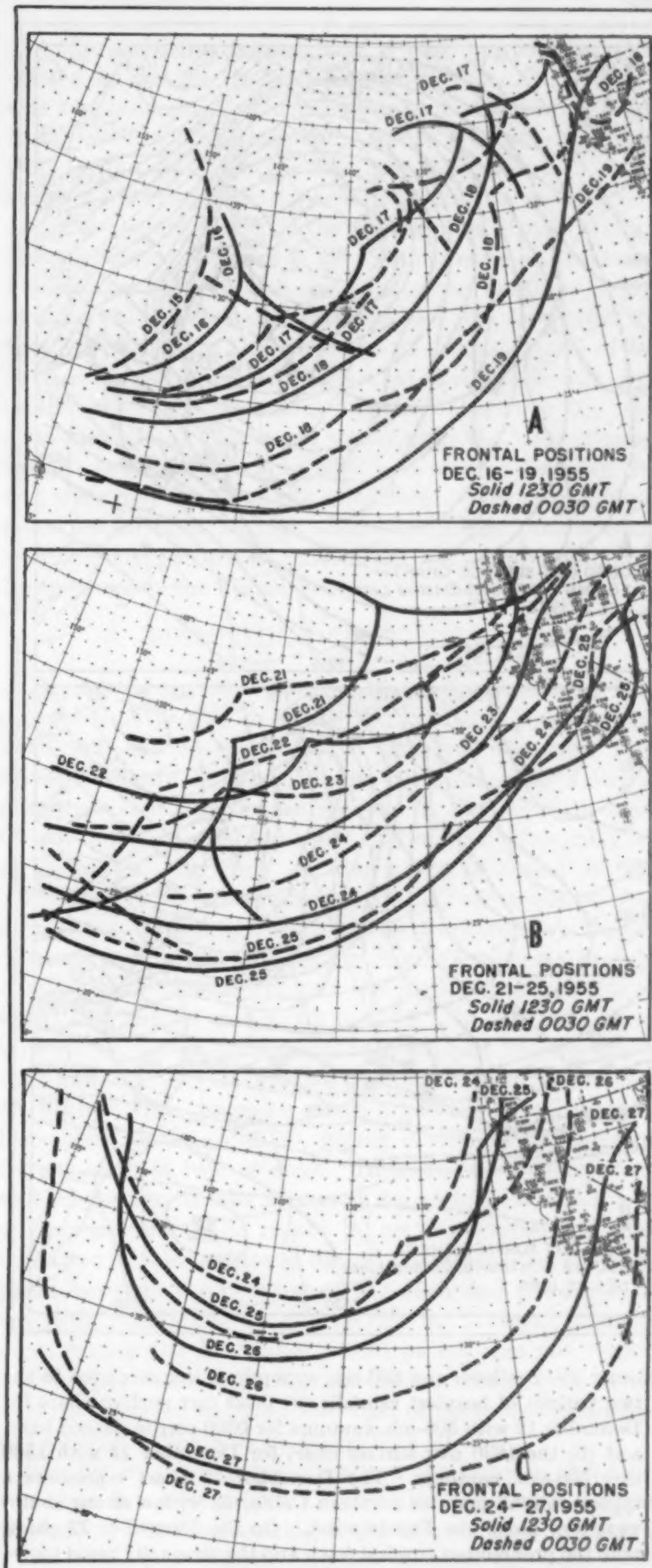

Figure 1.—The progression of frontal systems associated with the three main rain periods: (a) December 16–19, (b) December 21–25, and (c) December 24–27. Solid lines represent positions at 0430 PST and dashed lines 1630 PST. Fronts with the first two rain periods had a more southerly trajectory and moved faster than those in the final period.

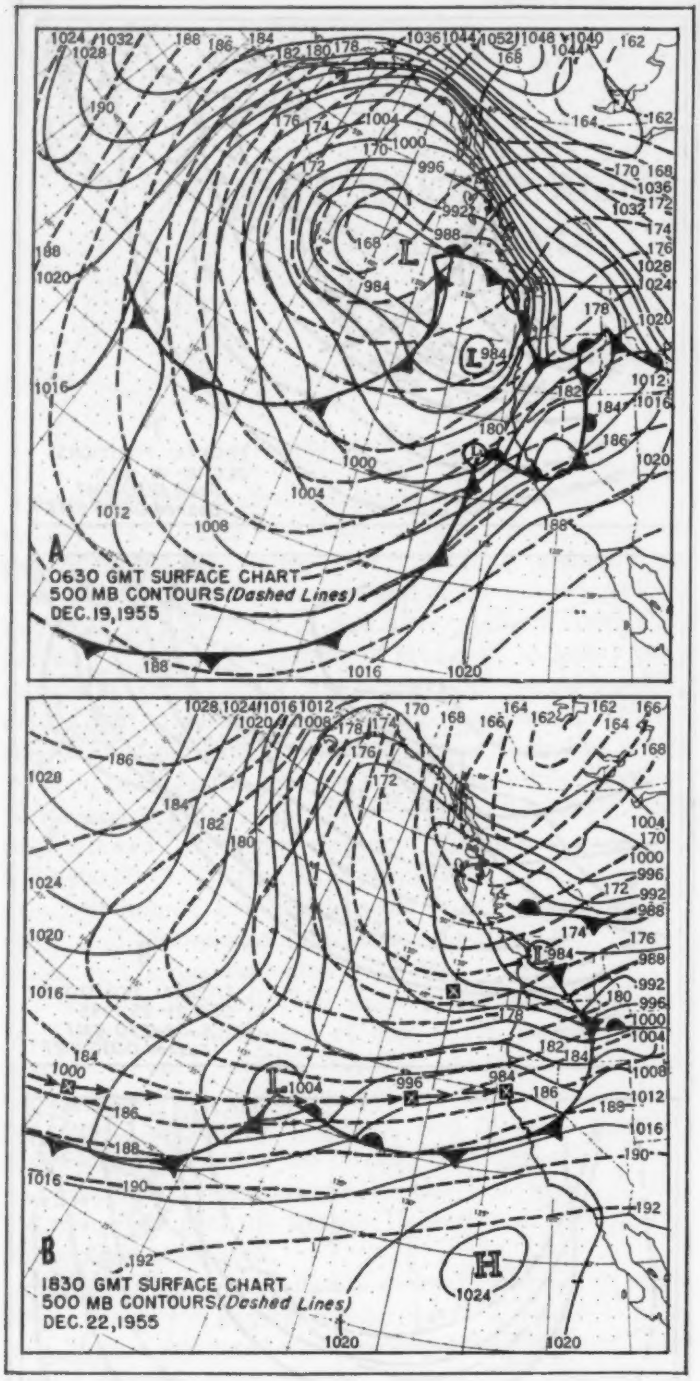

FIGURE 2.—Sea level and 500-mb. synoptic patterns related to the two periods of heaviest rainfall: (a) 0630 GMT surface chart for December 19 with 500-mb. contours for 0300 GMT in dashed lines, and (b) the 1830 GMT surface chart for December 22 with 1500 GMT 500-mb. contours. The December 19 chart represents a typical rainfall map for northern California with a strong southwest flow along the Pacific coast. On the December 22 chart, note the pronounced tropical fetch and the unusually rapid movement of the Pacific wave as indicated by its 6-hourly positions (squares).

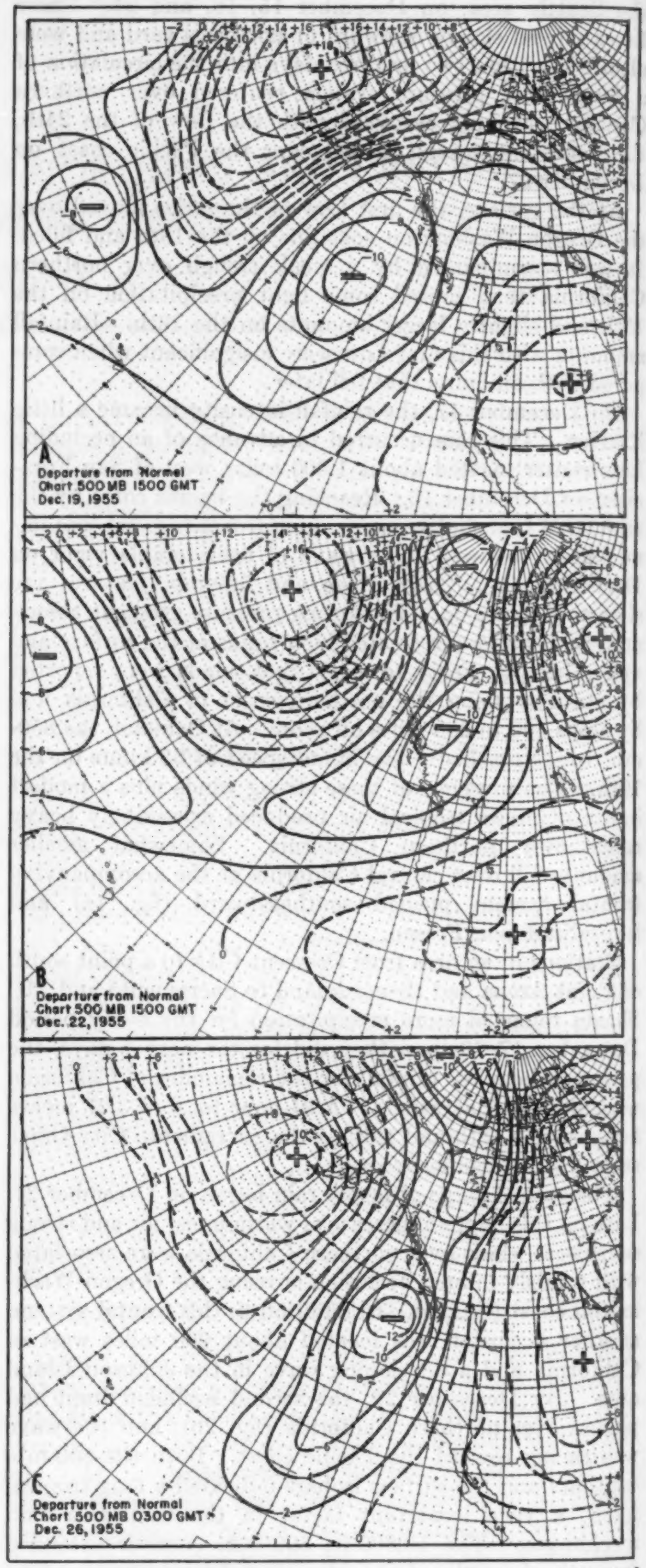

FIGURE 3.—Strength of blocking action in the Pacific is indicated by the departures of 500-mb. heights from normal for (a) 1500 GMT, December 19, (b) 1500 GMT, December 22, and (c) 0300 GMT, December 26. Values are in 100's of feet.

of North America. The wave from Johnson Island accelerated as it moved into this strong flow, traveling approximately 2,375 miles in 24 hours or nearly 100 m. p. h.

It was during this period that newspapers reported that 100 m. p. h. headwinds had almost halted all Pacific flights between California and Hawaii. One airline reported that the strong winds extended as low as 6,000 feet and that it was impossible to get over or around them. The anemometer on the Richmond-San Rafael Bridge registered 90 m. p. h. at 2230 P. S. T. on December 22 and again at 0200 P. S. T. December 23; at no time during that night was it less than 60 m. p. h.

This Low center was the most intense of the period, reaching a central pressure of 984 mb. just prior to passing onshore. As it moved rapidly eastward, Red Bluff reported its lowest sea level pressure on record. The intense precipitation attributed to this Low was largely due to the fact that it had a greater influx of moist tropical air than any of its predecessors. Too, in addition to strong orographic lifting, the tropical air was subjected to maximum lifting in the apex of the occluding warm sector located over northern California.

At Blue Canyon between December 21 and December 22, the 24-hour rainfall totaled 9.31 inches to set a new record. Their previous 24-hour maximum was 8.66 inches in November 1950. The progressive southward movement of the heaviest precipitation is shown in figures 9 and 10. This storm even broke rainfall records on the southern coast of California where Santa Maria, with a 13-year record, reported a 24-hour maximum of 3.07 inches between December 24 and December 25. This maximum broke the previous record of 2.55 inches established in January 1943.

On December 24, before the frontal systems from the previous storm had moved out of southern California (fig. 1b), synoptic features indicated that another surge of rainfall was imminent. At this time, a Low in the Gulf of Alaska began to dominate the situation by moving slowly southeastward and tightening the gradient over northern California. A weak occluded front pushed over the Pacific coast on December 25 (fig. 1c) and was followed approximately 24 hours later by a wave cyclone. This wave passed onshore near Ukiah, and its accompanying cold front was the last of the series to cross California. Coming from the Aleutian area and having a much shorter trajectory over warmer water than its predecessors, this Low system yielded about half as much rain as the others.

4. BLOCKING ACTION IN THE PACIFIC OCEAN

One of the most important broadscale features contributing to the extremely heavy rainfall in northern California was the blocking action of the 500-mb. High in the Aleutian area. The importance of this block is that it forced eastward-moving Pacific cyclones to take a southerly path over the warm Pacific Ocean. There the Lows gathered an influx of moist tropical air before proceeding to the North American coast.

Andrews [4] has written that a blocking tendency had existed in the North Pacific area since late October. It was not, however, until December 15 that the block began to achieve major proportions. Strong 500-mb. departures from normal heights were noted on December 19 (fig. 3a) ranging from a positive 1,800 ft. in the Bering Sea to a negative 800 to 1,000 ft. in the eastern Pacific trough. Large negative departures were also present in the south Pacific area. While not record departures, these values emphasized the strength of the block. On December 22, the departures (fig. 3b) were not as large as those of the 19th, but certainly indicated that the block was well established. By December 25, the departures (fig. 3c) showed that the block was weakening; the large departures in the Bering Sea had split, decreased to 1,000 ft., and were moving off to the southeast. This strong block persisted for 11 or 12 days, somewhat longer than normal, and thereby permitted more than the usual number of Lows to reach the Pacific coast.

5. DISTRIBUTION OF LOW CENTERS

During the period December 16–26, the number of Low centers that passed over the Pacific coast between San Francisco and Portland was larger than normal. It is shown in figure 4b that it is not uncommon for Lows to pass over this area during the winter months with most of the Lows entering the coast either near Crescent City or Portland. A study of storm tracks found in the *Monthly Weather Review* from 1940 to 1955 revealed that a maximum of eight Low centers have entered this stretch of coast during any one season from October to March. January, not December, had the highest incidence with four Lows in 1952 and again in 1941. In this case, three Low centers entered the coast between San Francisco and Portland, the largest number for any December in over 25 years. Low pressure centers reached the coast on December 16, 19, and 22, giving a time lapse between centers of three to four days. In order to find a comparable frequency, it was necessary to go back to the storm of March 1907. The report [5] on this storm said that three wave cyclones moved directly across the Sacramento Basin between the evening of the 16th and the night of the 19th, nearly one a day. While the interval between Lows during the December 16–26 period was not record breaking, it was a little shorter than normal. The usual interval for Lows entering the coast of northern California and Oregon appears to be about 5 to 10 days.

Another interesting feature about the Lows in this case was their intensity. The Low of the 22d had a central pressure of 984 mb., making it the deepest Low in twelve years. The total number of Lows to enter the coast each year since 1940 and their lowest pressure is shown in figure 4a. The deepest Low in the past fifteen years was 983 mb. in January 1943.

6. JET STREAM RELATIONSHIP

The position of the jet axis over the Pacific coast was

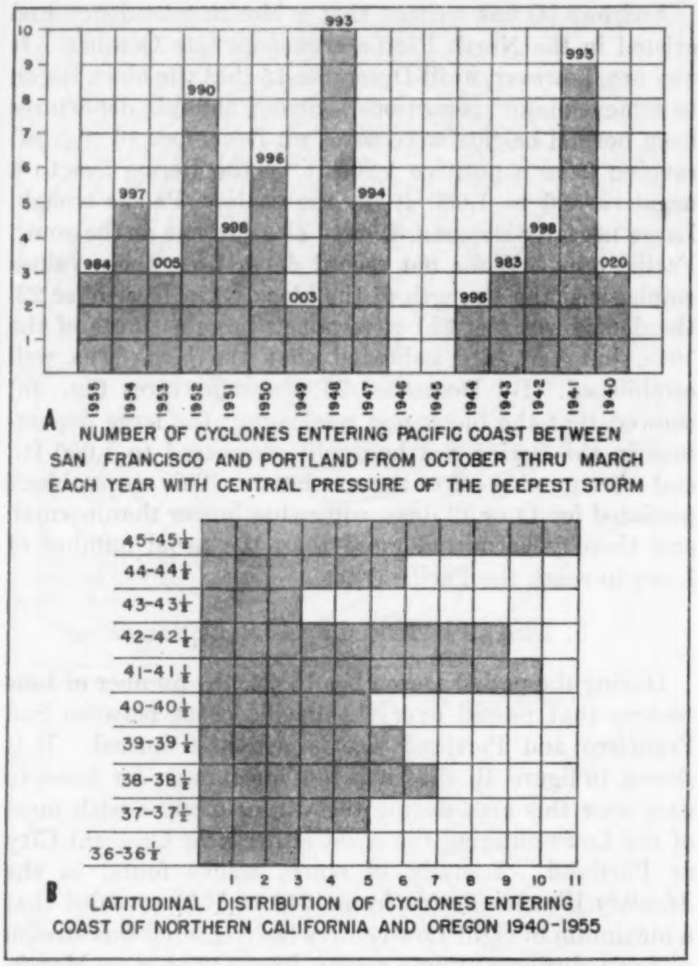

FIGURE 4.—(a) Annual number of Lows entering the Pacific coast between San Francisco and Portland since 1940 for the season October through March. Central pressure of the season's deepest storm is indicated above each bar. The 984-mb. Low of December 22 ranks with the intense Low of 1943. (b) Latitudinal distribution of Lows entering the northern coast of California and Oregon for the period 1940–1955.

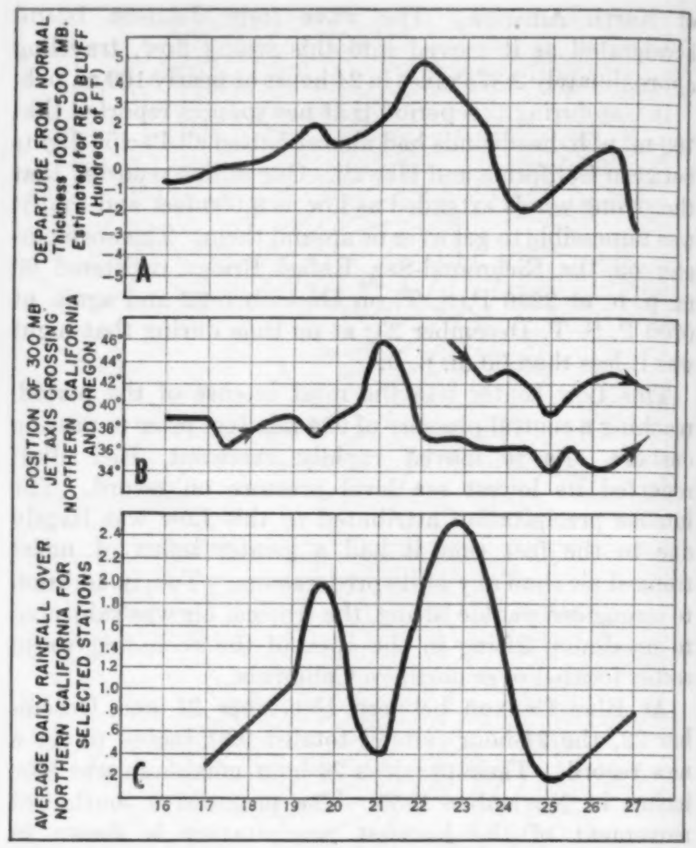

FIGURE 5.—Chronological relationship (a) estimated departures of 1,000–500-mb. thickness from normal, (b) latitudinal position of the 300-mb. jet axis over the Pacific coast, and (c) average daily rainfall for selected stations in northern and central California.

closely related to the rainfall intensity over northern and central California. Most of the heavy rainfall occurred north of 37° N. latitude, and the 300-mb jet axis appeared to be near this line during periods of intense precipitation. (figs. 5b and 5c). This pattern showed general agreement with Starrett's [6] model which placed the area of maximum precipitation ahead of a trough and just to the north of the jet stream with a secondary maximum south of the jet.

Heavy precipitation occurred on December 19 as the polar jet axis dropped to 37° N. On December 20–21, the rain decreased significantly as the jet stream shifted north to the Portland area. During the period of greatest average rainfall, December 22–23, the jet was located near 36° N., or south of Santa Cruz. As the jet continued to shift southward toward Santa Maria, the rain became lighter, but increased again by the 26th as the jet axis shifted northward. Wind velocities in the 300-mb. jet were 100 kt. or more during the periods of heavy rain and reached a maximum of 175 kt. on the night of December 21.

7. VERTICAL MOTION

When computed vertical velocities were compared with rainfall intensities, the results were rather disappointing. Vertical motion charts (fig. 6) were reproduced from the operational maps of the Joint Numerical Weather Prediction Unit and are representative of the 11-day period. The instantaneous vertical velocities plotted on the charts were computed in mm./sec., and the isopleths were drawn in cm./sec. Computation of these values incorporated only adiabatic and vorticity concepts; no provisions were made for orographic effects or convection in conditionally unstable air. These values were averaged over an area of approximately 150,000 square miles and do not represent maximum vertical motion.

On December 19, the second heaviest period of precipitation, the vertical motion at the 800-mb. level over northern California (fig. 6a) ranged from .5 cm./sec. to .8 cm./sec. At the 550-mb. level, vertical velocities were two or three times greater than those at 800 mb. (table 1). Investigations of vertical motion by Pennsylvania State University [7] have shown that an 800-mb. vertical ve-

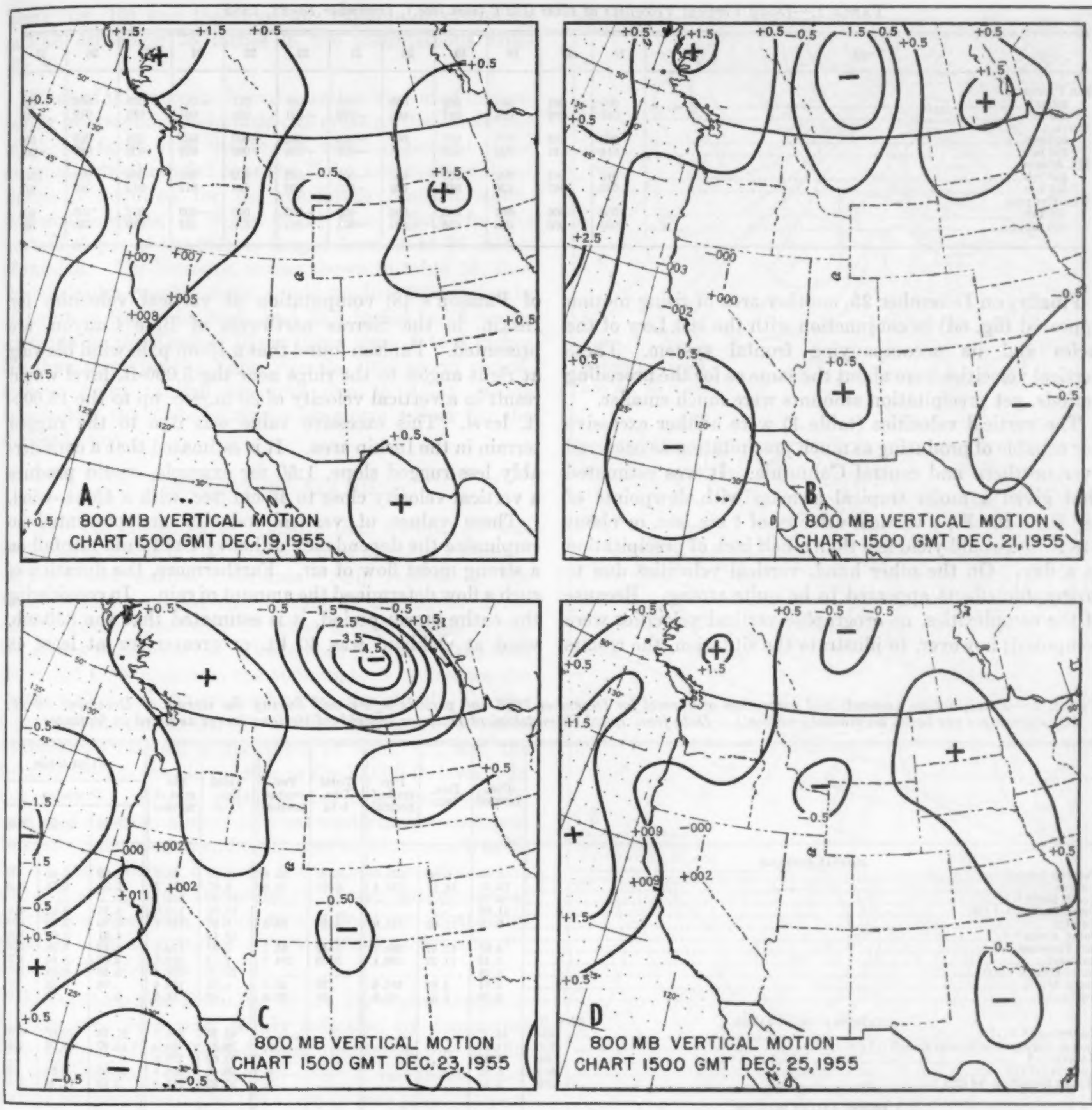

FIGURE 6.—1500 GMT charts of instantaneous vertical motion at 800-mb. level based on Joint Numerical Weather Prediction Unit computations with velocities analyzed in cm./sec. (a) December 19, (b) December 21, (c) December 23, and (d) December 25, 1955.

locity of .6 cm./sec. or more gives just about an even chance for rain or fair weather.

Vertical velocities for December 21 (fig. 6b) indicated downslope motion along the Pacific coast with little or no activity in the Sierras. Rainfall did decrease on this date, but continued to fall in significant amounts. On December 23 (fig. 6c), instantaneous velocities showed a maximum of 1.1 cm./sec. over the San Francisco area, only small velocities in the Sierras, and downslope motion at Eureka.

At the 500-mb. level (table 1), velocities on the 22d were seven to eight times greater than those at the 800-mb. level. This seemed to indicate that most of the lifting was occuring at the upper levels and was substantiated by the fact that the high-level Sierra stations received their greatest precipitation during this period (table 2).

TABLE 1.—*Daily Vertical Velocities at 1500 GMT (mm./sec.), December 16–27, 1955*

Date	16	17	18	19	20	21	22	23	24	25	26	27
San Francisco:												
800 mb	000	004	008	008	002	−002	−006	011	−000	009	005	−004
550 mb	001	009	024	017	000	−009	−021	024	003	023	012	−008
Eureka:												
800 mb	008	005	016	007	004	−003	−005	−000	002	009	007	000
550 mb	014	011	029	016	014	−007	−006	003	012	028	023	−001
Mt. Shasta:												
800 mb	010	003	009	007	000	−000	−002	002	001	−000	009	005
550 mb	020	007	026	018	008	−002	000	016	012	012	029	014
Blue Canyon:												
800 mb	000	−000	004	005	−000	000	−003	002	−003	002	005	000
550 mb	004	−000	020	013	−001	−004	−011	013	007	010	020	008

Finally, on December 25, another area of rising motion appeared (fig. 6d) in conjunction with the last Low of the series and its accompanying frontal system. These vertical velocities were about the same as for the preceding periods, yet precipitation amounts were much smaller.

The vertical velocities (table 1) were neither excessive nor capable of producing as much precipitation as occurred over northern and central California. It was estimated that given a moist tropical airmass with dewpoints of 58° F. to 60° F., a vertical velocity of 1 cm./sec. or about 118 ft./hr. would yield less than a half inch of precipitation in a day. On the other hand, vertical velocities due to orographic effects appeared to be quite strong. Because of the complexities, no orographic vertical velocities were computed; however, to illustrate the situation, the results of Paulson's [8] computation of vertical velocities for Inskip, in the Sierras northwest of Blue Canyon, are presented. Paulson found that a 45-m. p. h. wind blowing at right angles to the ridge near the 3,000-ft. level would result in a vertical velocity of 30 m./sec. up to the 15,000-ft. level. This excessive value was due to the rugged terrain in the Inskip area. It is estimated that a considerably less rugged slope, 1:50 for example, would produce a vertical velocity close to 40 cm./sec. with a 45-kt.-wind.

These values of vertical velocity are presented to emphasize the dependency of heavy California rainfall on a strong moist flow of air. Furthermore, the duration of such a flow determined the amount of rain. In considering the entire storm period, it is estimated that the 850-mb. wind at Oakland was 40 kt. or greater for at least 48

TABLE 2.—*Precipitation amounts and percentage of normal for December 1955 and periods before and during the storms of December 16–26. All percentages are based on monthly normals. Data from Local Climatological Data for individual stations except as noted in footnotes*

	Elev. (ft.)	Dec. normal	Dec. 1955	Percent of normal	Total Dec. 1–14	Percent of normal	Total Dec. 15–28	Percent of normal	4-Day totals, December 17–20	21–24	25–28
COASTAL STATIONS											
Tatoosh Island		6.96	9.00	129.3	4.90	70.4	4.10	58.9	1.00	2.49	.51
Astoria		13.21	16.57	125.4	6.66	50.4	9.87	74.7	2.31	4.75	1.27
North Bend [1, 2]		9.79	------	------	------	------	17.20	175.7	------	------	------
Crescent City [1, 2] (16)		11.90	------	------	------	------	13.09	110.0	4.10	3.93	4.46
Eureka		6.09	11.63	191.0	3.26	53.5	8.35	137.1	3.70	2.73	1.68
Point Arena [1, 2]		------	------	------	------	------	10.42	------	4.51	3.04	1.89
San Francisco		4.07	11.47	281.8	3.49	85.7	7.31	179.6	1.42	4.28	1.37
Oakland		3.42	11.29	330.1	3.56	104.1	7.52	219.8	2.03	3.54	1.75
Santa Cruz [1, 2] (17)		4.24	------	------	------	------	12.78	301.4	2.10	8.91	1.73
Santa Maria		2.61	4.82	184.6	.73	28.0	4.03	154.4	.04	3.32	.67
Burbank		2.86	1.31	45.8	.88	30.8	.42	14.9	0	.24	.18
STATIONS IN COAST RANGE											
Cummings [1, 2] (17)	1324	13.47	------	------	------	------	45.26	336.0	21.18	19.05	6.03
Skaggs Springs Los Lomas Ranch [1, 2] (08)	1930	11.57	------	------	------	------	20.31	353.3	13.07	13.05	2.37
Hobergs [1, 4]	2980	11.43	------	------	------	------	31.60	276.5	------	------	------
Angwin [1, 2] (19)	1815	5.81	------	------	------	------	26.40	454.4	16.05	9.23	.02
Mount Hamilton [1, 2] (22)	4209	5.01	------	------	------	------	15.93	317.9	3.10	11.44	1.39
INLAND VALLEY STATIONS											
Medford	1312	3.13	8.77	280.2	2.12	67.7	5.73	83.1	1.59	4.12	.17
Vollmers [1, 4]	1359	11.53	------	------	------	------	18.62	161.5	------	------	------
Red Bluff	341	4.23	7.71	182.3	3.24	76.6	4.25	100.5	2.46	.64	.73
Sacramento	25	3.19	12.20	382.4	1.79	56.1	10.13	317.6	4.37	3.82	1.61
Fresno	331	1.63	6.73	412.9	1.95	119.3	4.60	282.2	.21	3.63	.76
Bakersfield	480	1.03	.50	48.5	.42	40.8	.08	7.8	0	.01	.06
STATIONS ALONG SIERRAS											
Mount Shasta	3544	5.39	17.48	324.3	2.29	42.5	14.86	275.7	6.18	5.77	2.81
Downieville [1, 4]	2965	10.51	------	------	------	------	26.95	256.4	------	------	------
Deer Creek [1, 2] (17)	3700	10.96	------	------	------	------	37.32	340.5	12.44	19.73	4.12
Blue Canyon	5280	8.75	45.12	515.7	8.48	96.9	35.82	409.4	11.48	19.20	3.97
Calaveras Big Trees [1, 2] (08)	4696	8.95	------	------	------	------	28.55	318.9	7.99	16.86	3.70

[1] Preliminary report, data incomplete.
[2] From synoptic teletypewriter reports, supplemented by data on River Services Daily Maps, figured for 24-hr. periods starting at 0400 PST.
3 From [11].
[4] From [12], Dec. 26, 1955.
( ) Time (PST) at which each 24-hr. period ends.

hours (fig. 10) and therefore was capable of producing rainfall exceeding 25 inches in the mountainous areas (fig. 8).

Winds of this magnitude and duration were used in computing orographic precipitation as great as that described in [5]. In figure 61 of that report, about 40 percent of the seasonal normal rainfall over the Yuba and Feather River Basins is required for the maximum possible storm. Seasonal normals, in figure 22 of that report, for the western slopes of the Sierras ranged from 50 to 90 inches of rainfall. Furthermore, it was shown in table 59, that the maximum possible storm would produce 20.0 inches in 48 hours in the Yuba basin and 23.6 inches in 72 hours. Amounts in the Feather River Basin were 5 to 6 inches less than those for the Yuba. In the 1955 storm period, 48-hour point rainfall amounts due to 45-kt. winds approached the 72-hour maximum storm values for the smaller basins.

8. TEMPERATURE FEATURES

There was considerable evidence that tropical air was available to assist in the production of the heavy rains in northern and central California. Ship reports off the Pacific coast reported dew points in the upper fifties except around December 22 when several values in the low sixties were observed. Vederman [9] has written that the —20° C. isotherm at the 500-mb. level delineates the northern limit of the tropical air at that level. On the night of December 21, P. S. T., Oakland's 500-mb. temperature reached a maximum of —11° C., and the freezing level in the Sierras rose to the 12,000-ft. level. In this same period, rain was reported near the 10,000-ft. level at Yosemite, a most unusual wintertime occurrence. In the four-day period ending December 23, as much as 2½ feet of snow melted away at the higher elevations. At well-exposed sites on December 22, it was estimated that melt water was being added to the flood runoff at daily rates as high as 4 inches at the 5,500-ft. level and 1.7 inches at the 7,000-ft. level.

During the period December 16–26, the overall temperature features were most clearly indicated by departures from normal of the 1000–500-mb. thickness. A 200-ft. rise in thickness is equivalent to a 5.4° F. rise in the mean virtual temperature of the thickness column [10]. Departures for northern and central California were more than 200-ft. above normal during the peak rain periods of December 19 and 22 (figs. 7a and 7b). Somewhat cooler air prevailed on the 26th (fig. 7c), and less rainfall was noted than for the preceding periods. Daily departures were estimated for Red Bluff and plotted on figure 5a for comparison with daily precipitation amounts and the latitudinal position of the jet stream over the Pacific coast. As would be expected, the period of greatest average rainfall coincided with the period of warmest air; Red Bluff reached a maximum departure of 500 ft. above normal on December 21, PST.

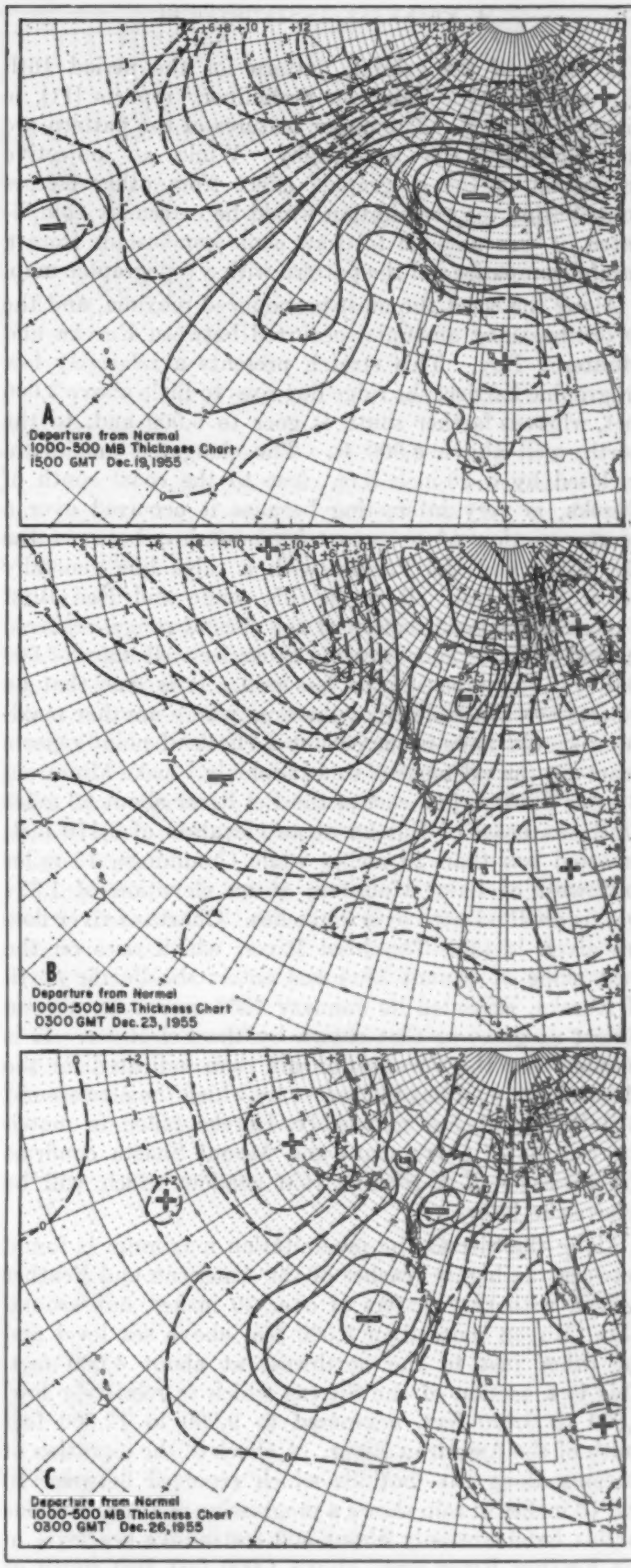

FIGURE 7.—Overall temperature features are represented by the departures of the 1,000–500-mb. thickness from normal: (a) 1500 GMT, December 19, (b) 0300 GMT, December 23, and (c) 0300 GMT, December 26, 1955. Values are in 100's of feet.

9. RAINFALL DISTRIBUTION

A chart of the rainfall pattern for the period 16th through the 24th based on preliminary reports [11], is given in figure 8. The major features of the pattern are controlled by the topography. While an objective separation of the orographic effect from other factors contributing to precipitation would be extremely complicated, it was possible to draw some conclusions from a careful comparison of the pattern with a topographic map.

Along the coast the most pronounced maxima, and the record-breaking amounts, occurred between Eureka and Monterey Bay. This stretch presents a relatively low orographic barrier; the ridge line rises to little above 3,000 feet, whereas farther south it goes to 5,000 and, to the north, well above 5,000 ft. The elongated maximum, enclosed by a 30-inch line, close to the coast south of Eureka, is very interesting because it occurred over a narrow section of the coastal mountains, between the Eel River and the Pacific, with a ridge line generally below 3,000 feet. Between this range and Red Bluff a more widespread section of the coastal range, centered around Mount Linn, presents a barrier well above 5,000 feet, yet this area showed less rain. It is true that no reports are available from the area where another maximum should have occurred but a check of point reports bears out the existence of some anomaly. Lake Mountain Ranger Station, just east of the Eel River about 60 miles south-southeast of Eureka at an elevation of 3,170 feet, reported less than 20 inches while Cummings, 15 miles southwest of Lake Mountain at an elevation of 1,324 feet, is credited with over 35 inches. Charts of river flow are given in [5]. The Mad River, which rises on the west slope of Mount Linn and enters the Pacific north of Eureka, exceeded its January 1953 record by a ratio almost as great as that shown by the Eel River. It is possible that there was more rain than indicated for the Mount Linn area but the extent by which the area around Red Bluff and, less noticeably, Eureka failed to match the records of Sacramento and Mount Shasta confirms the presence of a relative rain shadow which will be referred to later.

Along the Sierras the precipitation maximum is found between the higher reaches of the American and Feather Rivers, with two centers of over 30 inches, one around Blue Canyon more than 5,000 feet above sea level and the other just to the northwest at about 4,000 feet. This is a section of the Sierras which is relatively low, 7,000 to 9,000 feet, compared to 9,000 to 12,000 feet south of the American River. A check of the elevation of stations along the foothills which reported between 10 and 15 inches of rain shows a progressive relation; stations in this band are only about 500 feet above sea level in the Feather River area, above 1,000 feet just south of the American River, and above 2,000 feet northeast of Fresno.

The distribution of precipitation at Red Bluff was rather

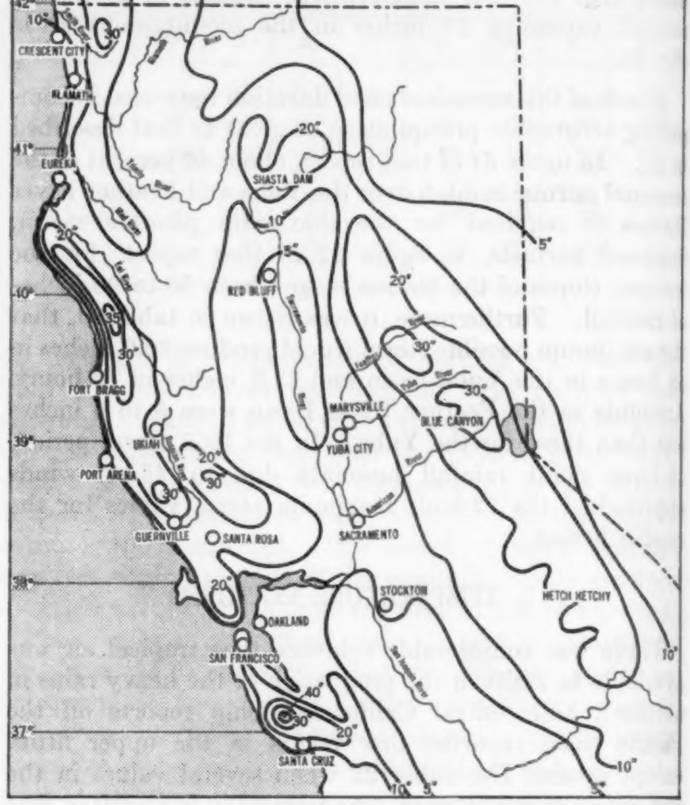

FIGURE 8.—Isohyet map of central and northern California for the period December 16–24 inclusive, reproduced from a report prepared by the Corps of Engineers [11] and based on preliminary data. Strong orographic influences are indicated by the large rain maxima along the mountain ridges.

unique. During December 15–27, rainfall there was above December normal, yet adjacent stations (table 2) reported considerably more than their normal—up to four times more. Sacramento, having similar normals, is considered a reasonable comparison in this case. In the past, the rainfall distribution at Red Bluff has been largely attributed to the direction of flow and to the presence of a cool dome over the area in advance of warm fronts [5]. During the peak rain periods in this case (fig. 10), Oakland's average 850-mb. wind was from 210° on December 19, 240° on December 23, and 210° on December 26. More precipitation fell at Red Bluff in the first and last rain period than on the 23d, showing a dependency on south-southwesterly winds. Too, more rain occurred during the December 17–20 period, since that situation featured the only good warm frontal surface (fig. 1a) to pass over northern California. Undoubtedly, the smaller amounts reported on the 26th were mostly due to less available moisture than for the preceding periods.

Another interesting aspect of Red Bluff's precipitation was that the rainfall appeared to be closely related to the position of the storm track with respect to the station. On December 19, the track of the waves was to the north

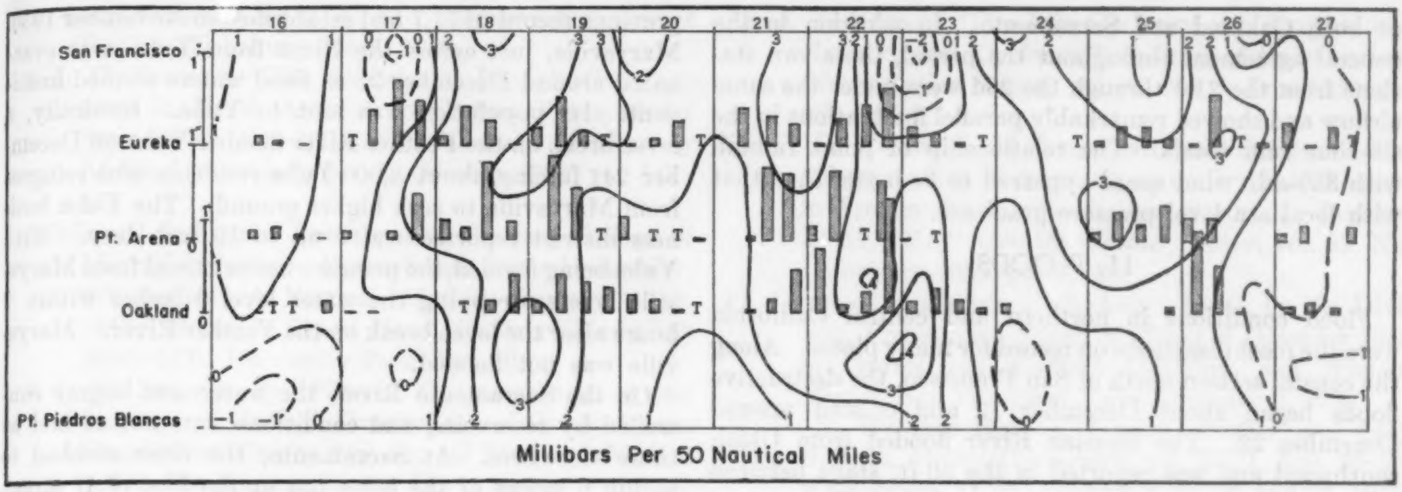

Figure 9.—Bar graph of 6-hour rainfall totals at Eureka, Point Arena and Oakland, superimposed on a time chart of the intensity of the sea level pressure gradient between eight coastal stations: North Bend, Crescent City, Eureka, Point Arena, San Francisco, Salinas, Point Piedras Blancas, and Santa Maria. Solid lines represent lower pressure to the north. Units are 1 mb. per 80 miles or approximately 15 knots onshore component of the gradient wind. December 16–27, 1955.

of Red Bluff and their rainfall was quite heavy. On the 22d, the track was nearly over the station and precipitation amounts were comparatively small. As the track shifted southward, precipitation amounts at Red Bluff were not significantly greater than those of the 22d, but Fresno incidentally, received their largest rainfall of the storm period.

10. LOW LEVEL FLOW

On the isohyetal map (fig. 8) it is seen that the importance of strong low-level flow is reflected in the rain maxima along the mountain ridges. To determine the significance of strong low-level flow at stations of low elevation, graphs were constructed comparing pressure gradients with point rainfall amounts. Bar graphs of the 6-hour rain totals at three coastal stations are presented in figure 9 and at four inland valley stations in figure 10.

On the bar graphs in figure 9 is superimposed a time-latitude analysis of the sea level pressure gradient along the coast. Pressure gradients were determined at 12-hour intervals for neighboring pairs of eight coast stations, from North Bend to Santa Maria. A smoothed analysis of the gradient values was made in units of 1 mb. per 80 miles. Solid lines represent lower pressure to the north, or an onshore component of the geostrophic wind of about 15 kt. per unit.

Three bands of strong gradient appeared, December 17–19, December 21–23, and December 24–26. Each coincided with the periods of heaviest rainfall. Point Arena and Oakland responded to the gradient increases but Eureka was erratic.

With the bar graphs in figure 10 is presented a time graph of the speed of the 850-mb. wind over Oakland. It can be seen that the rise and fall of this speed corresponds very closely to the overall fluctuation of rainfall

Figure 10—Bar graph of 6-hour rainfall totals at Medford, Oreg., Red Bluff, Sacramento, and Fresno, Calif. (scale given on left). Superimposed in single fluctuating line is graph of speed of 850-mb. wind over Oakland, (scale given on right). December 16–27, 1955.

at both Oakland and Sacramento. In addition to the general agreement throughout the period, these two stations from the 21st through the 23d were under the same airflow and showed remarkably parallel fluctuations in the six-hour rain totals. The relationship of point rainfall with 850-mb. wind speed appeared to be better than that with local sea level pressure gradients.

11. FLOODS

Flood conditions in northern and central California were the most disastrous on record for many places. Along the coastal section north of San Francisco, the destructive floods began about December 19 and crested around December 22. The Russian River flooded from Ukiah southward and was reported in the 50-ft. stage between Guerneville and the ocean. Its maximum discharge at Guerneville was 90,100 cu. ft./sec. Farther to the north, practically the entire Eel River was in flood, especially after the Redwood Valley Dam on the upper portion of the river overflowed. The development of a log jam in the river aggravated the situation also. At Scotia, the Eel River discharged a maximum flow of 500,000 cu. ft./sec., exceeding its previous record of 345,000 cu. ft./sec. established in December 1937. Both the Mad River and the Klamath River were higher than the record set in January 1953. In the town of Klamath, water was reported 15 to 18 feet deep as the Klamath River discharged 400,000 cu. ft./sec., beating its previous record by nearly a third. The Smith River and several smaller streams were also on rampage and exceeded their record flood stages.

Communities along the Eel River and the Klamath River were hit especially hard by the floods. Five small towns with populations close to 500 were reported "smashed" or "wiped out": Elinor, Pepperwood, and Weott on the Eel and Klamath, and Klamath Glen on the Klamath River. At Pepperwood, scarcely any house was reported on its foundation, and those houses not washed away were smashed.

South of San Francisco, creeks and rivers were also out of their banks, but the floods were not as severe as those in the north. Santa Cruz reported three deaths and 6 feet of water in the business district as the San Lorenzo Creek overflowed, reaching its greatest height since February 1940. A little to the north along the peninsula, more than 1,000 people were forced to evacuate their homes in Palo Alto when the San Franasquita Creek spilled over its banks and pushed two feet of mud and water into many homes lying in low areas. Some flooding was also reported in Burlingame, South San Francisco, Piscadero, and Linda Mar.

Beginning around December 22, flood conditions prevailed in the Sacramento Valley, and nearly every place reported record-breaking stages except on those streams where runoff was controlled by reservoirs. Perhaps, the most important flooding occurred along the lower reaches of the Feather River. At Yuba City, the Feather reached a flood stage of 82.4 feet on December 24, exceeding the previous record of 71.7 feet established in November 1950. Marysville, just across the River from Yuba, was evacuated around December 21 as flood waters seemed imminent. Its population was sent to Yuba. Ironically, a levee break on the Feather River flooded Yuba on December 24, forcing about 8,000 Yuba residents plus refugees from Marysville to seek higher ground. The Yuba business district reported water up to 15 feet deep. With Yuba being flooded, the pressure was removed from Marysville levees, dropping the water level 9 inches within 2 hours after the levee break on the Feather River. Marysville was not flooded.

On the Sacramento River, the water was largely controlled by reservoirs, and conditions were not as bad as those elsewhere. At Sacramento, the river climbed to within 6 inches of the levee top at the foot of H street, reaching a stage of 28.7 feet on December 23. Record flood stage at Sacramento was established in November 1950 with 30.2 feet.

Flooding was also reported at Stockton on the San Joaquin River system. Again, most of the streamflow was controlled and the river stages did not exceed the record of December 1950. Approximately 3,000 people were forced from their homes in Stockton as 3 to 4 feet of water poured into the southeastern section of the town on December 24.

By December 24, rivers in northern and central California had crested and flood waters were receding. West coast newspapers reported extensive damage and described the floods as the worst in history. They added that the storm period was characterized by a heavy almost continuous downpour that caused a runoff so great that the natural watershed could not handle it.

REFERENCES

1. E. M. Vernon, "An Objective Method of Forecasting Precipitation 24–48 Hours in Advance at San Francisco, California," *Monthly Weather Review*, vol. 75, No. 11, November 1947, pp. 211–219.
2. D. E. Martin and H. F. Hawkins, Jr., "The Relationship of Temperature and Precipitation over the United States to the Circulation Aloft. Studies of Winter Precipitation," *Weatherwise*, vol. 3, No. 6, December 1950, pp. 138–141.
3. G. D. Hughes and C. L. Roe, "Heavy Rainfall During Mid-January, Along the Pacific Coast," *Monthly Weather Review*, vol. 81, No. 1, January 1953, pp. 20–25.
4. J. F. Andrews, "The Weather and Circulation for December 1955—A Month With a Major Pacific Block and Contrasting Extremes of Weather in the United States," *Monthly Weather Review*, vol. 83, No. 12, December 1955.
5. Hydrometeorological Section, U. S. Weather Bureau, in cooperation with the Corp of Engineers, U. S. Army, "Maximum Possible Precipitation Over the Sacramento Basin of California," *Hydrometeoro-*

logical Report No. 3, U. S. Waterways Experiment Station, Vicksburg, Miss., 1943.
6. L. G. Starrett, "The Relation of Precipitation Patterns in North America to Certain Types of Jet Streams at the 300-millibar Level," *Journal of Meteorology*, vol. 6, No. 5, October 1949, pp. 347–352.
7. Mineral Industries Experimental Station, College of Mineral Industries, Pennsylvania State University, "Properties of Vertical Motion January 1–10, 1953," *Scientific Report* No. 1, Contract No. AF19 (604)–1025, University Park, Pa., 50 pp.
8. J. B. Paulson, Jr., "Storm Characteristics of the Sacramento Basin," *Transactions* of the American Geophysical Union, 22d Annual Meeting, Parts 1 and 2, Washington, D. C., July 1941, pp. 111–117.
9. J. Vederman, "The Life Cycles of Jet Streams and Extratropical Cyclones," *Bulletin of the American Meteorological Society*, vol. 35, No. 6, June 1954, pp. 239–244.
10. C. L. Kibler, C. M. Lennahan, and R. H. Martin, "Temperature Forecasting as an Implicit Feature in Prognostic Charts—A Case Study for January 23–31, 1955," *Monthly Weather Review*, vol. 83, No. 1, January 1955, pp. 23–30.
11. Corps of Engineers, U. S. Army, South Pacific Division, *Preliminary Report of Floods of December 1955 in Central and Northern California and Western Nevada*, San Francisco, Calif., January 9, 1956.
12. U. S. Weather Bureau, *Weekly Weather and Crop Bulletin, National Summary*, vol. XLII, Nos. 50–52, Washington, D. C., December 12, 19, and 26, 1955.

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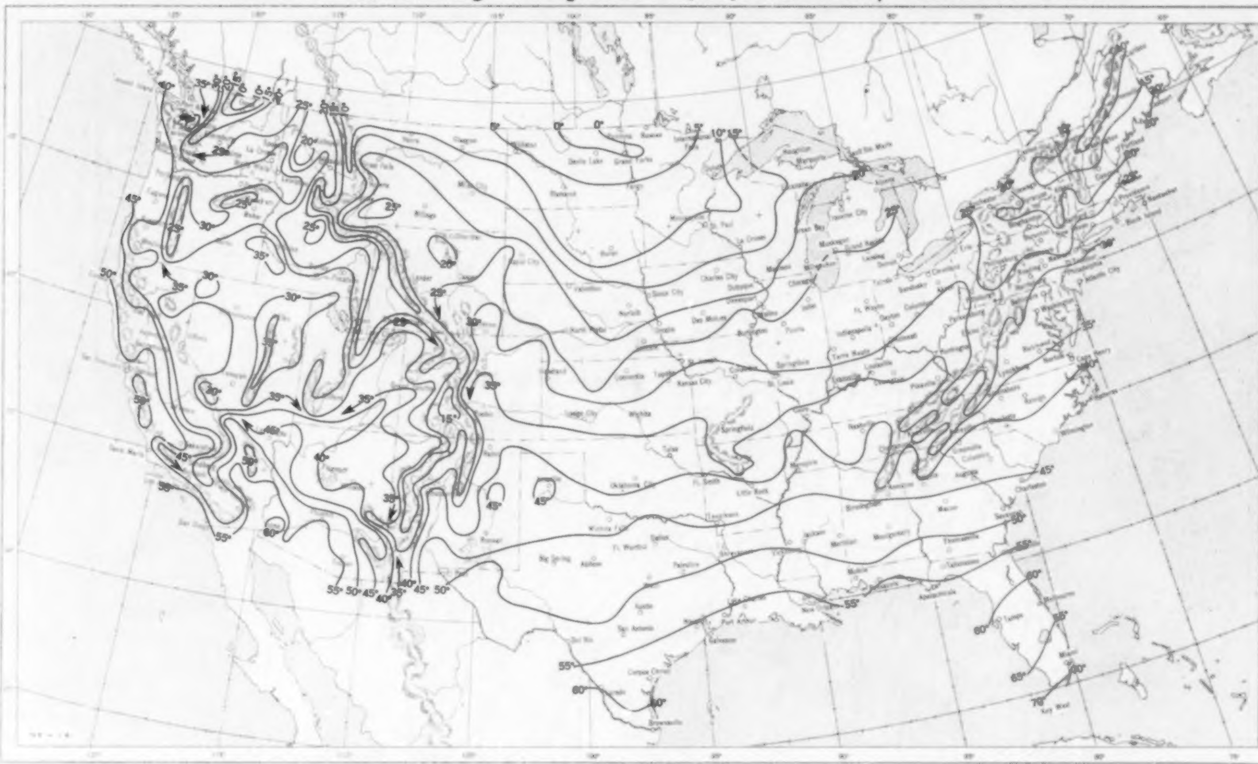
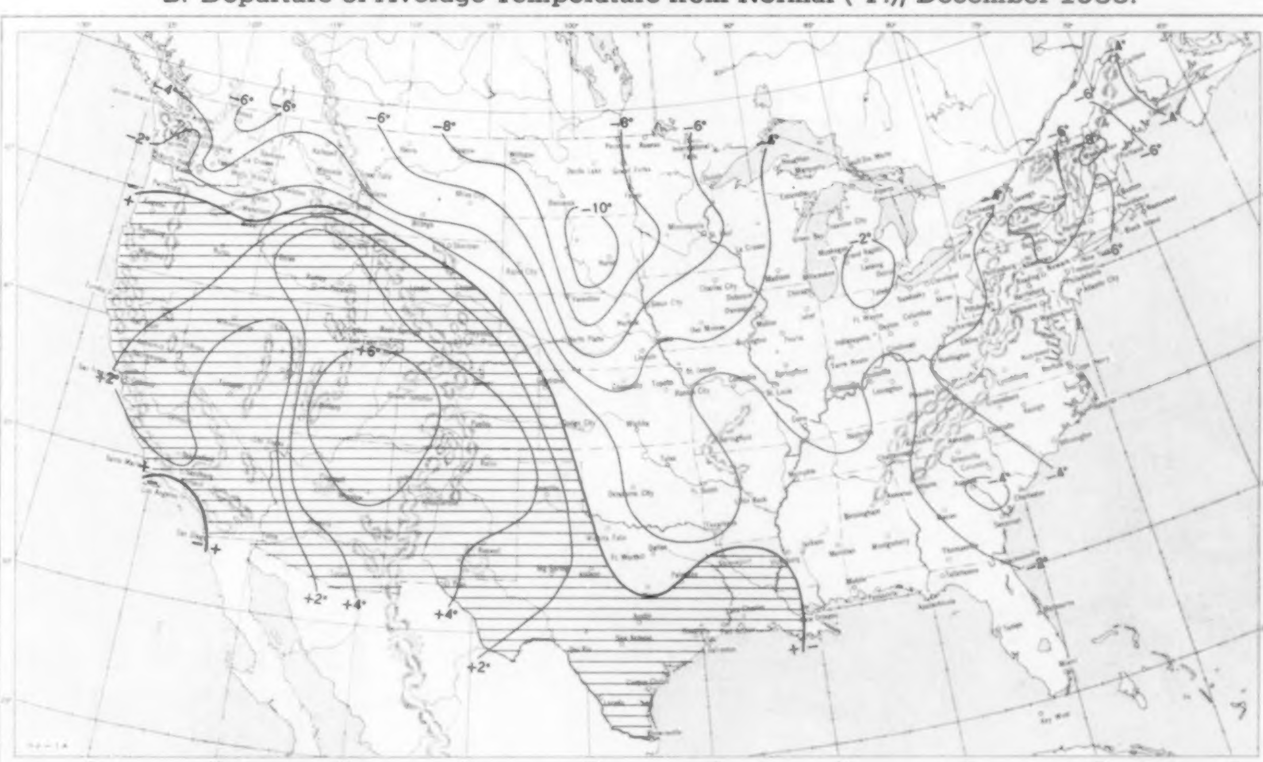
Chart I. A. Average Temperature (°F.) at Surface, December 1955.

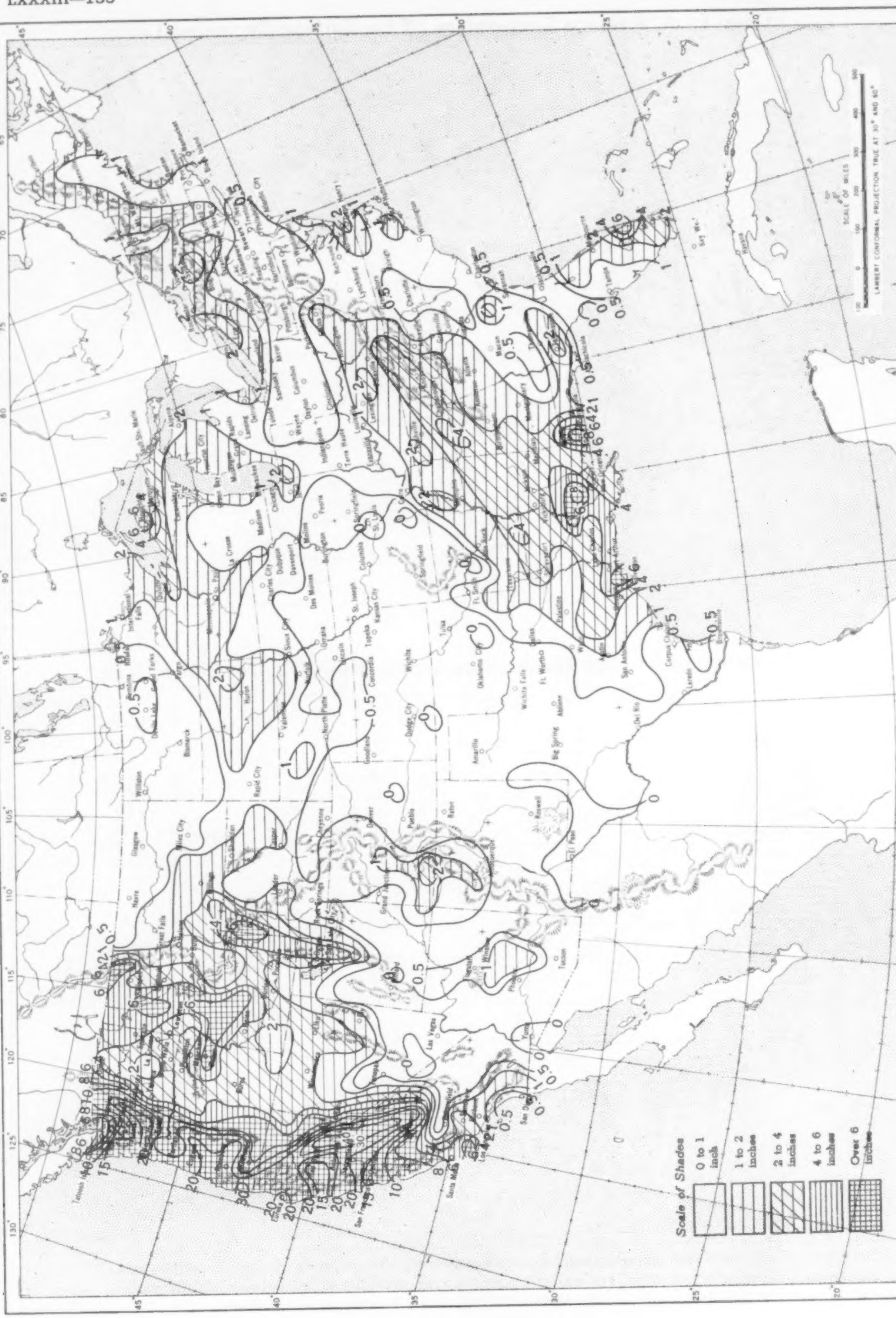


B. Departure of Average Temperature from Normal (°F.), December 1955.



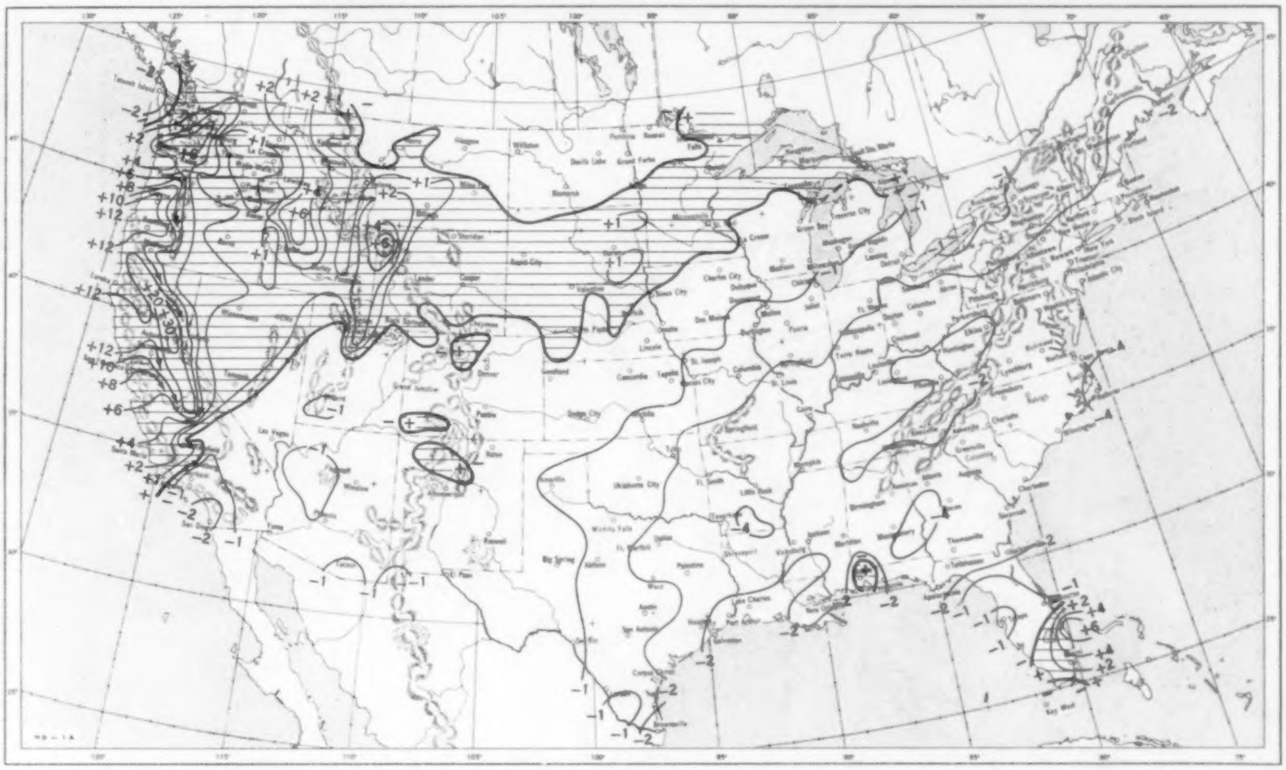
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), December 1955.

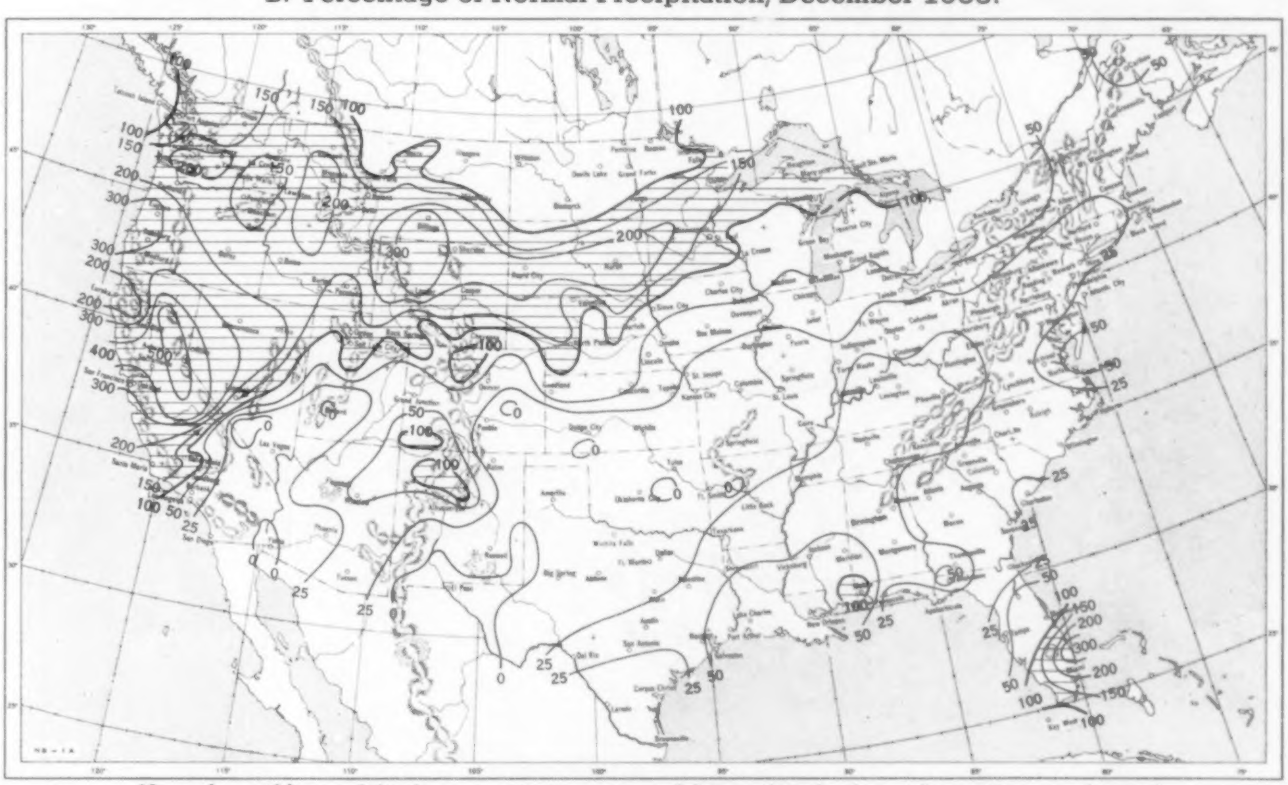


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), December 1955.

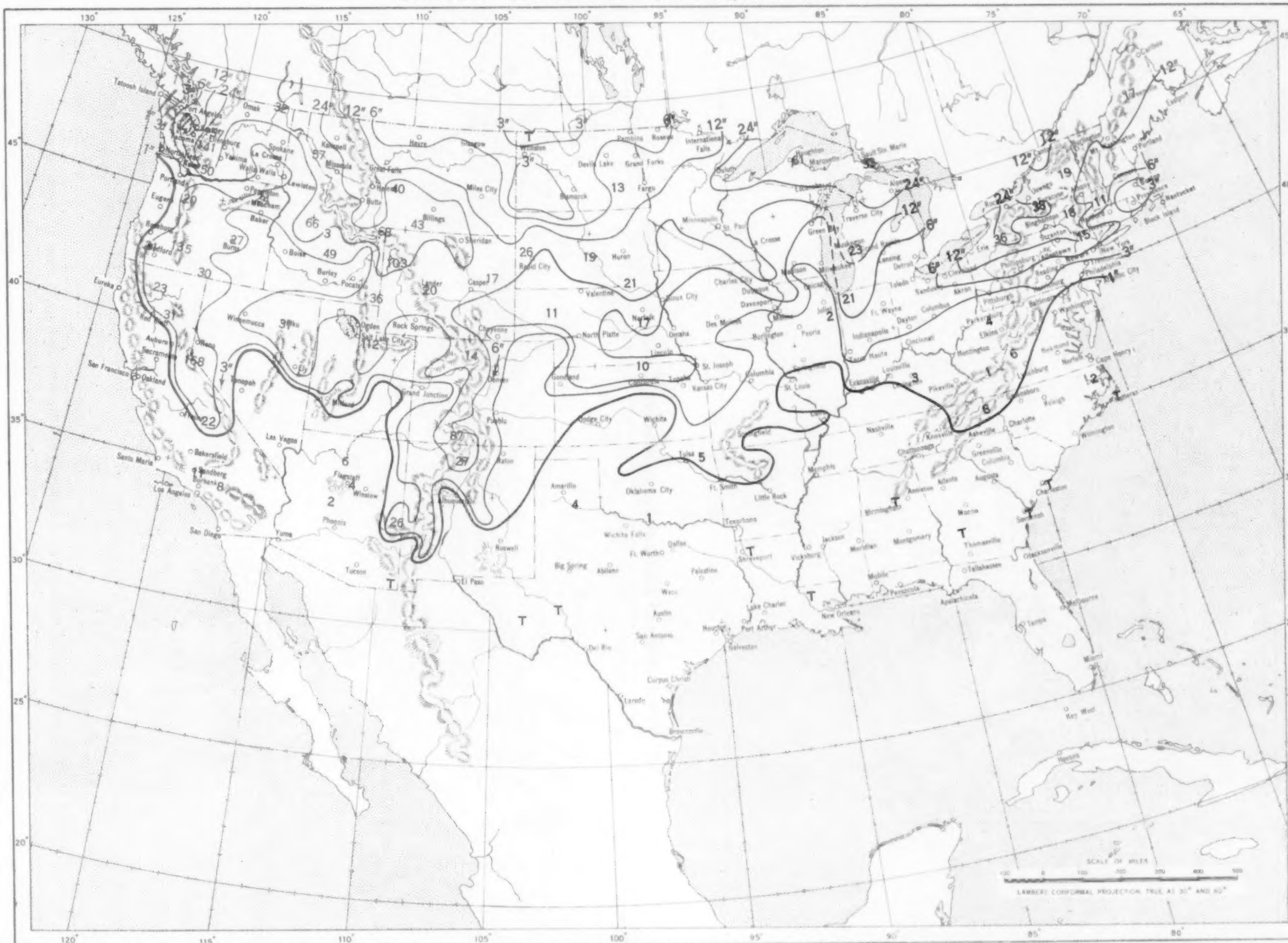


B. Percentage of Normal Precipitation, December 1955.



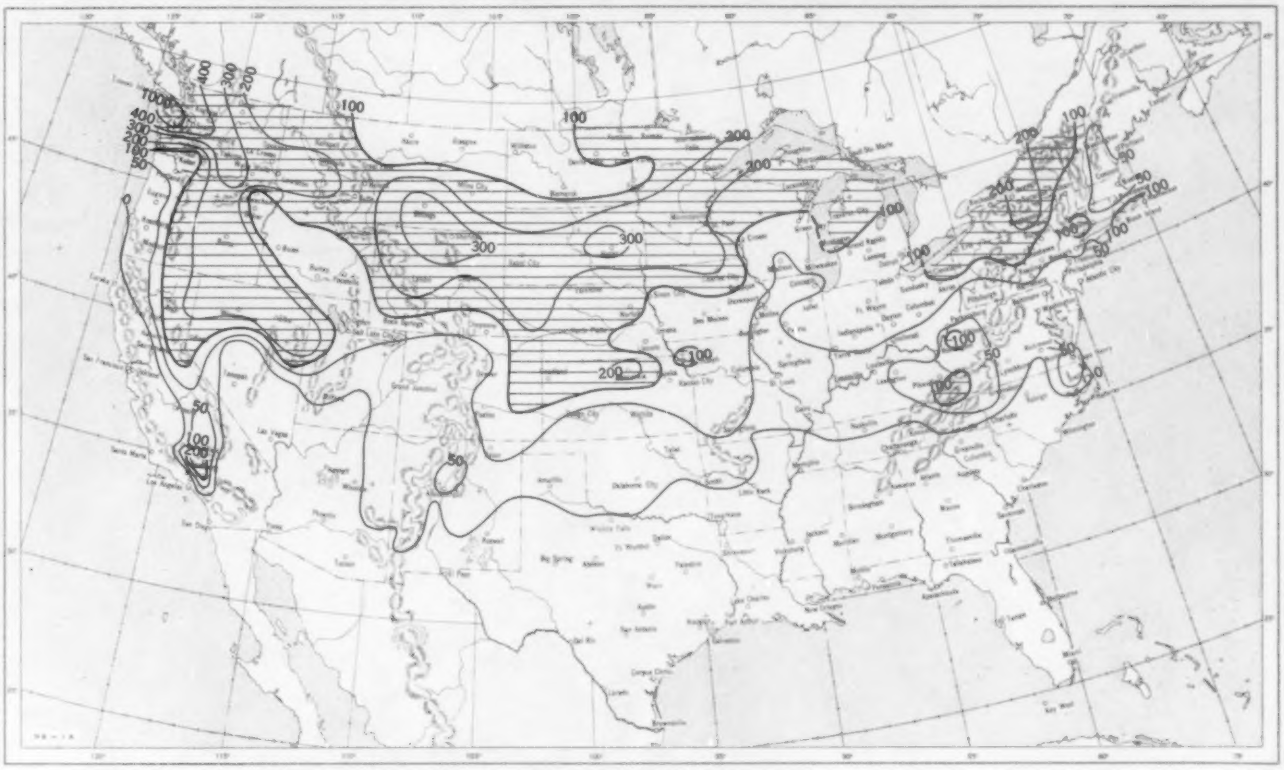
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), December 1955.

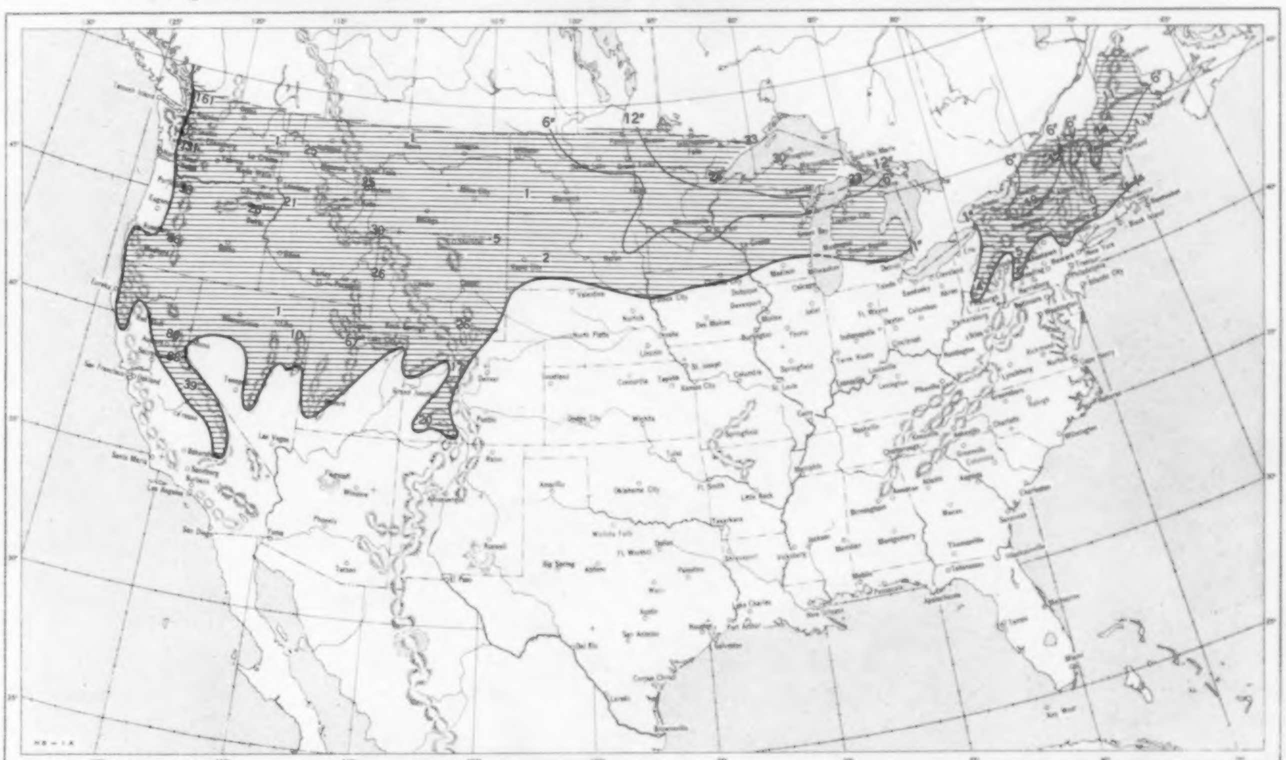


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, December 1955.

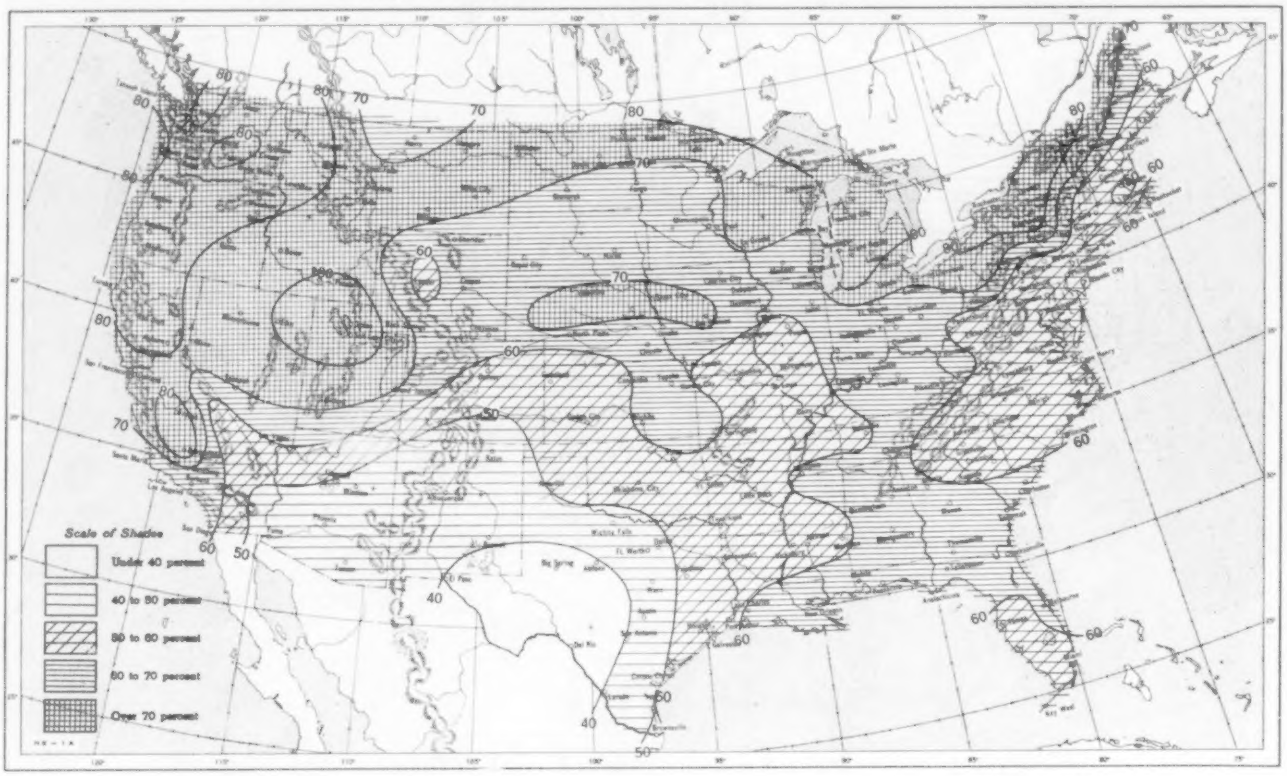


B. Depth of Snow on Ground (Inches). 7:30 a. m. E. S. T., December 26, 1955.

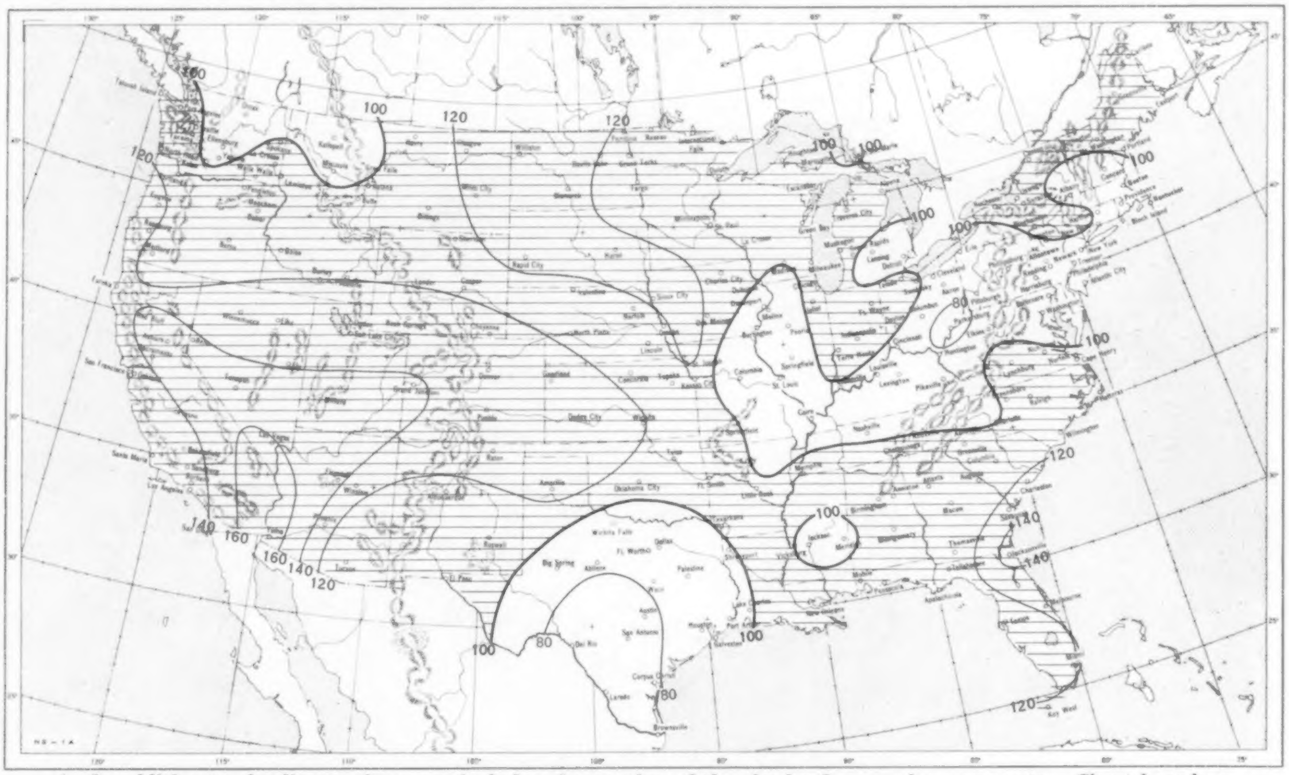


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, December 1955.

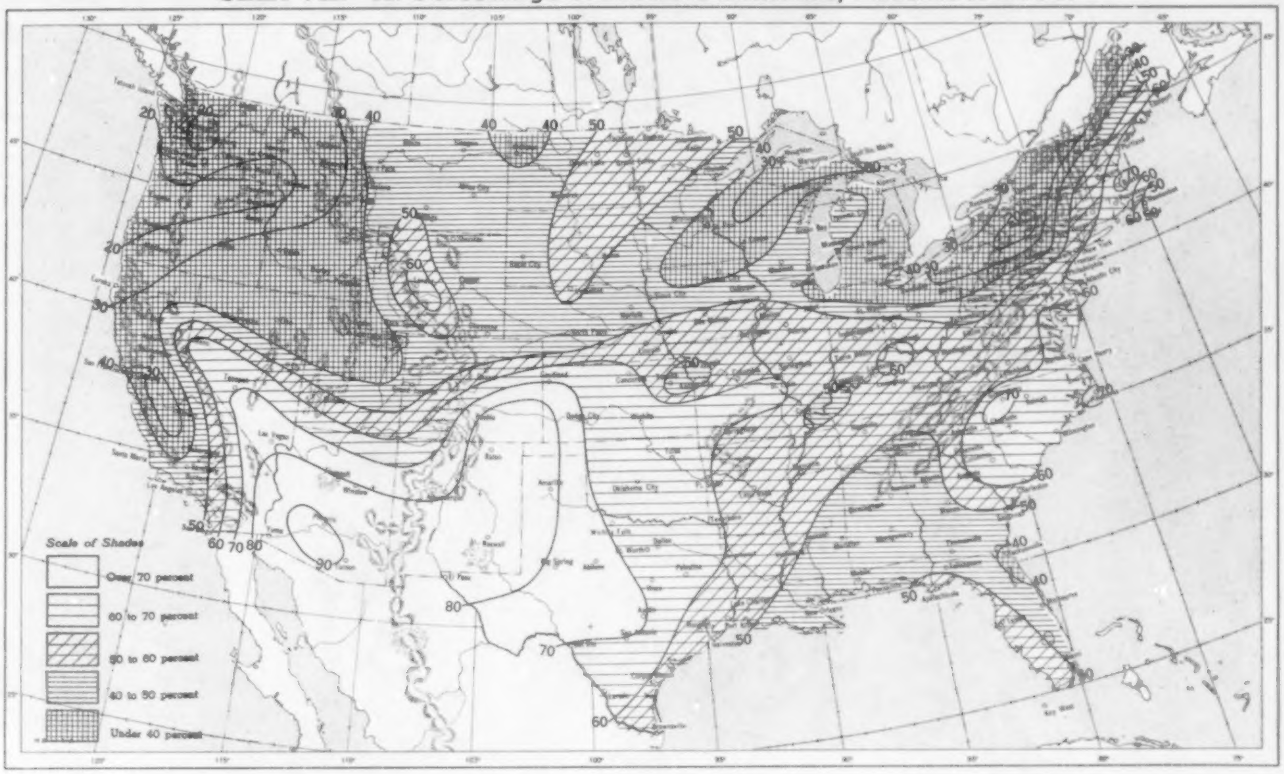


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, December 1955.

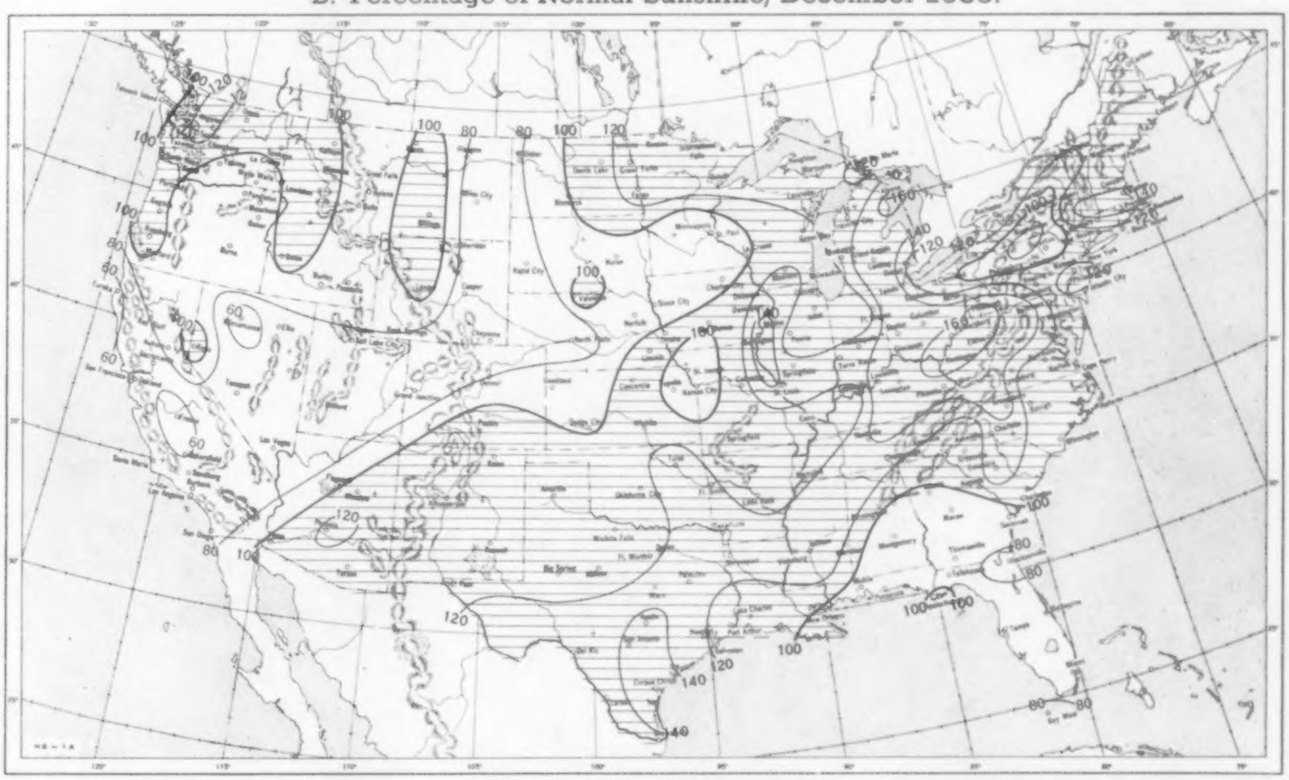


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, December 1955.



B. Percentage of Normal Sunshine, December 1955.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, December 1955. Inset: Percentage of Normal Average Daily Solar Radiation.

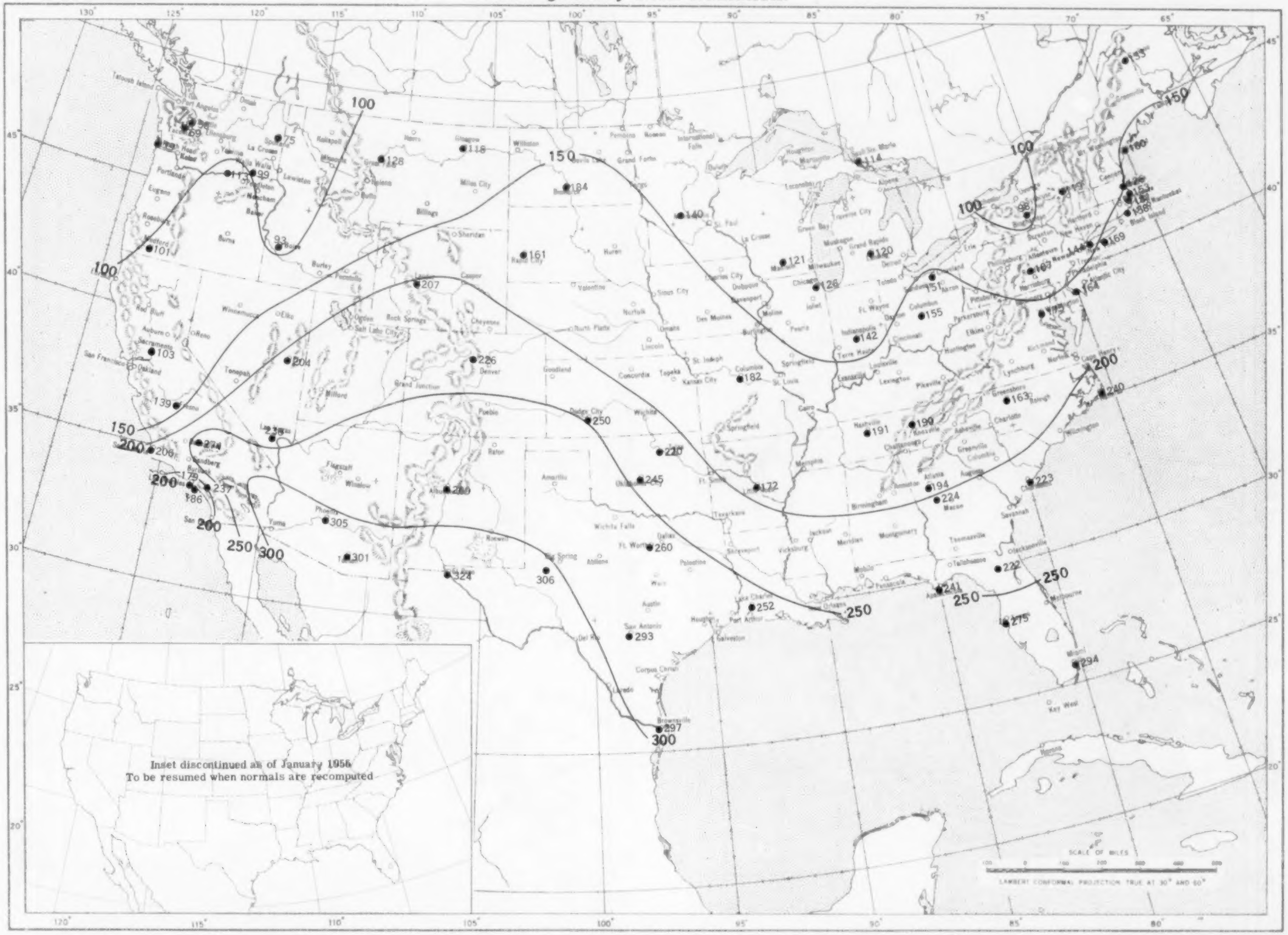
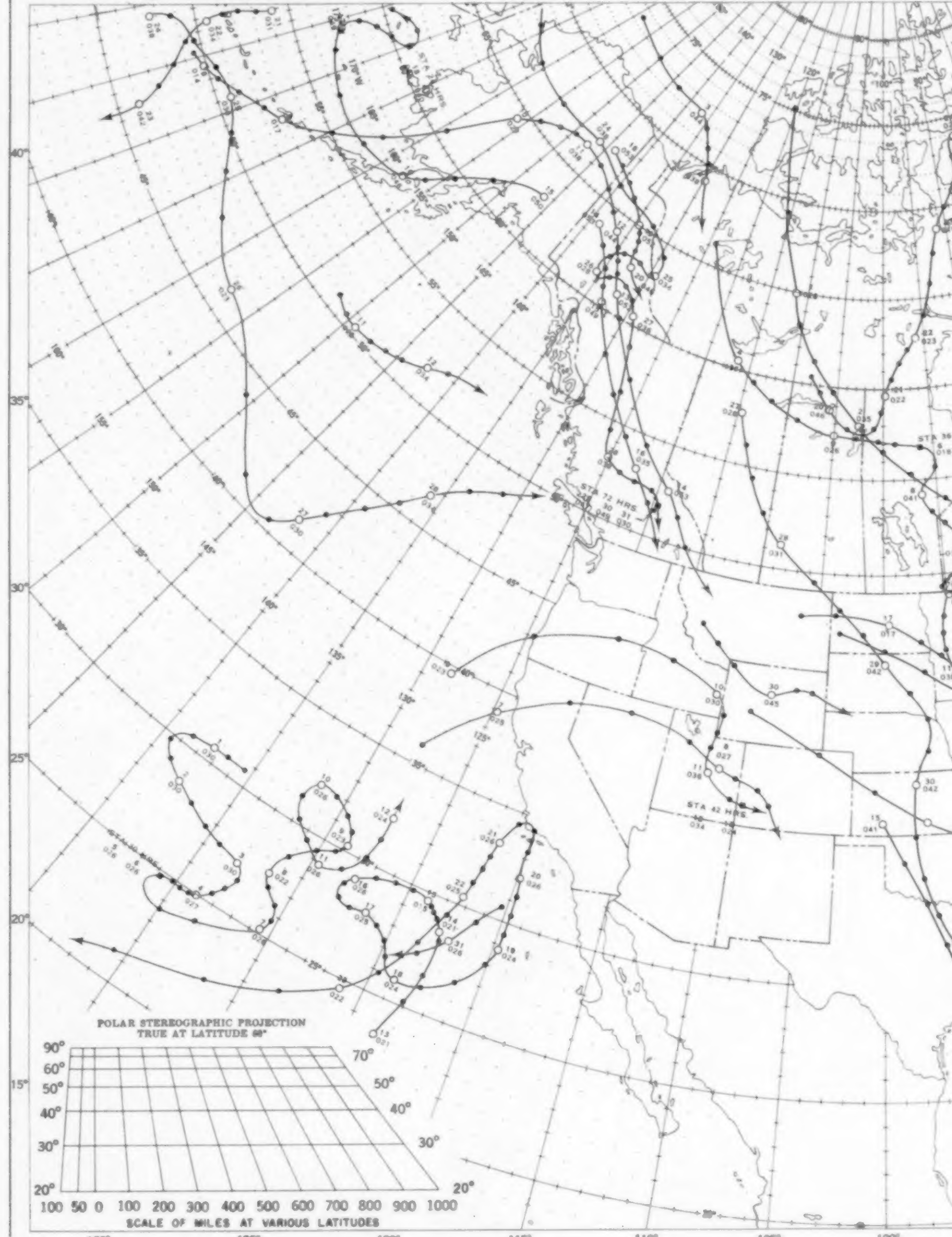


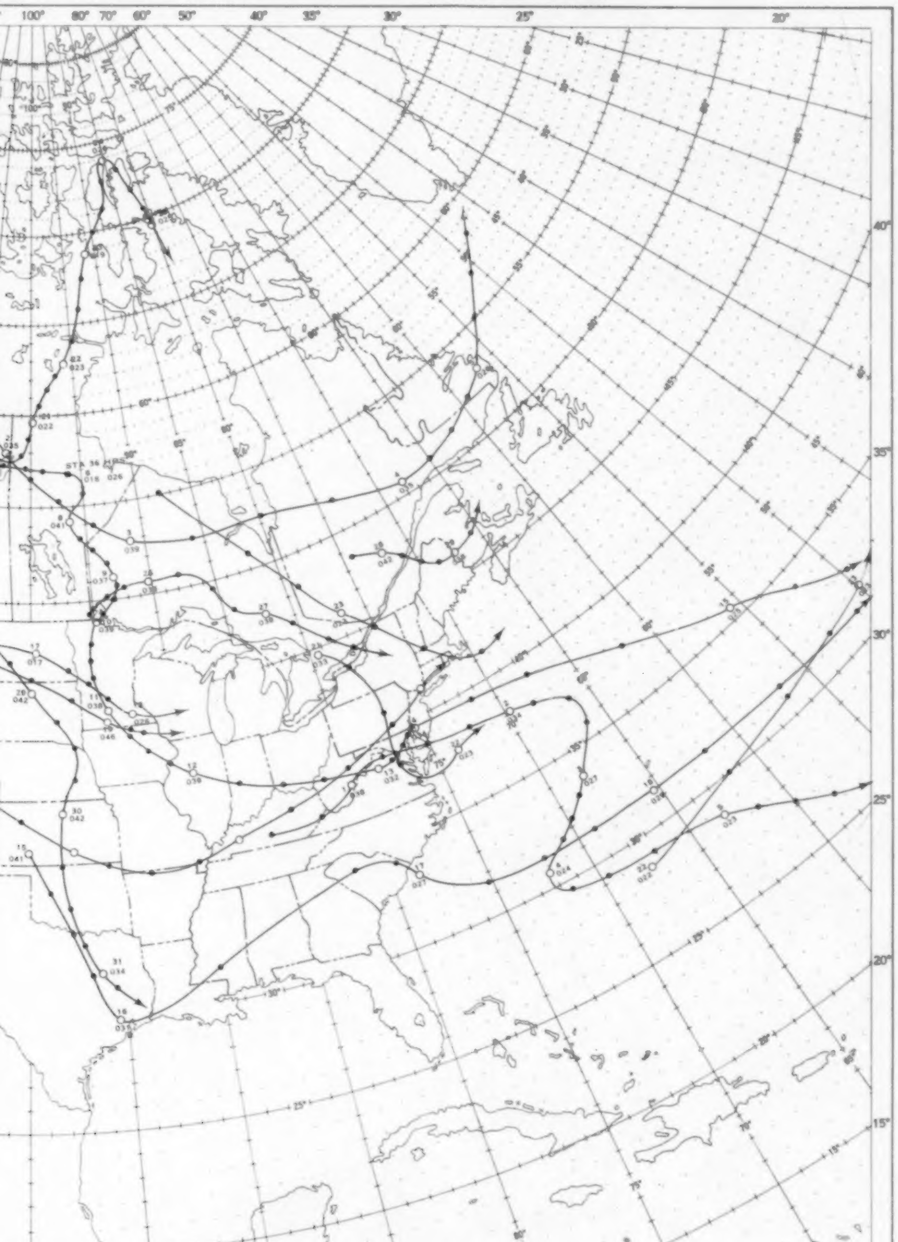
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.$^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at S



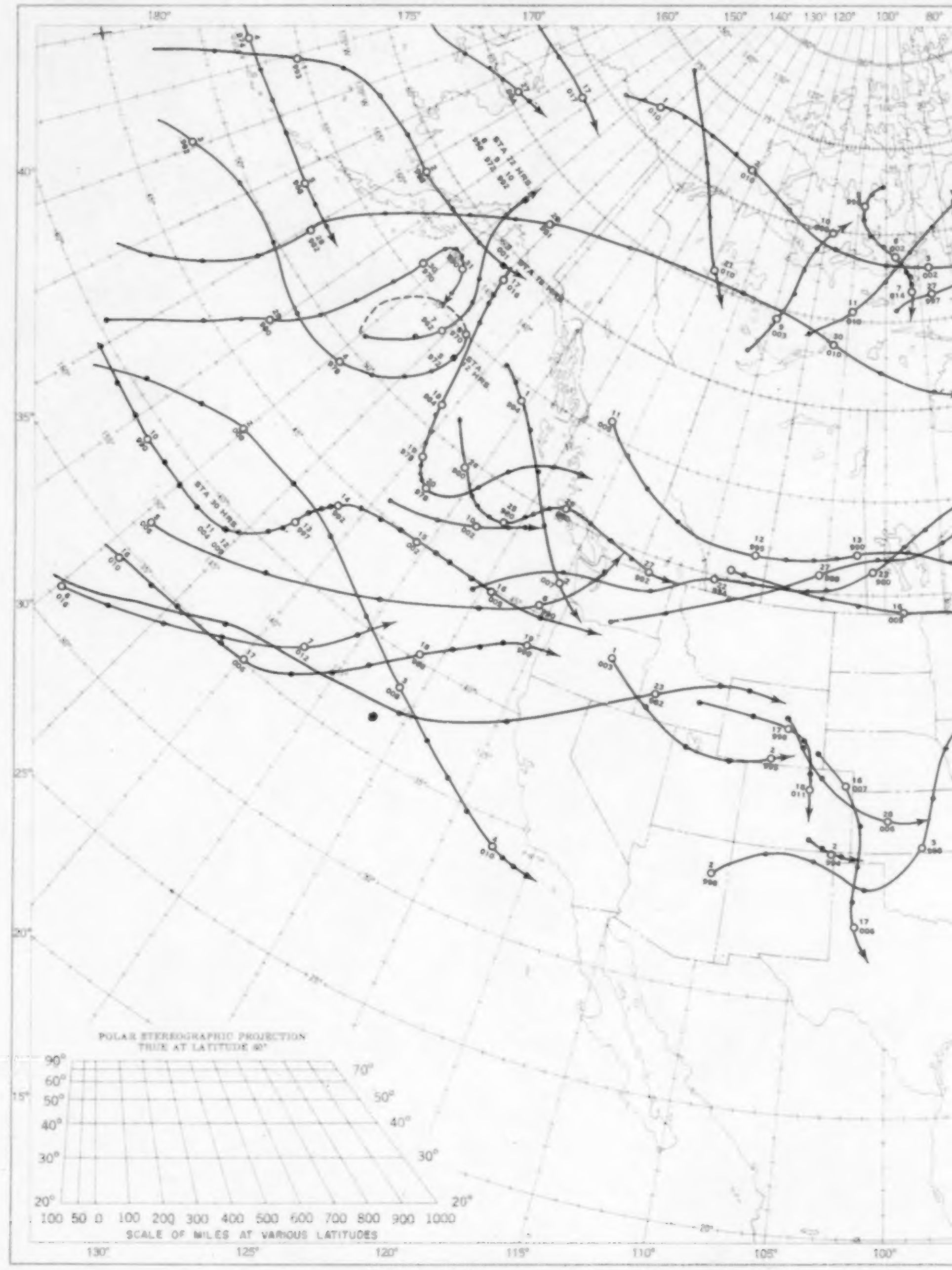
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circ
Dots indicate intervening 6-hourly positions. Squares indicate position of
indicates reformation at new position. Only those centers which c

nes at Sea Level, December 1955. (Corrected)



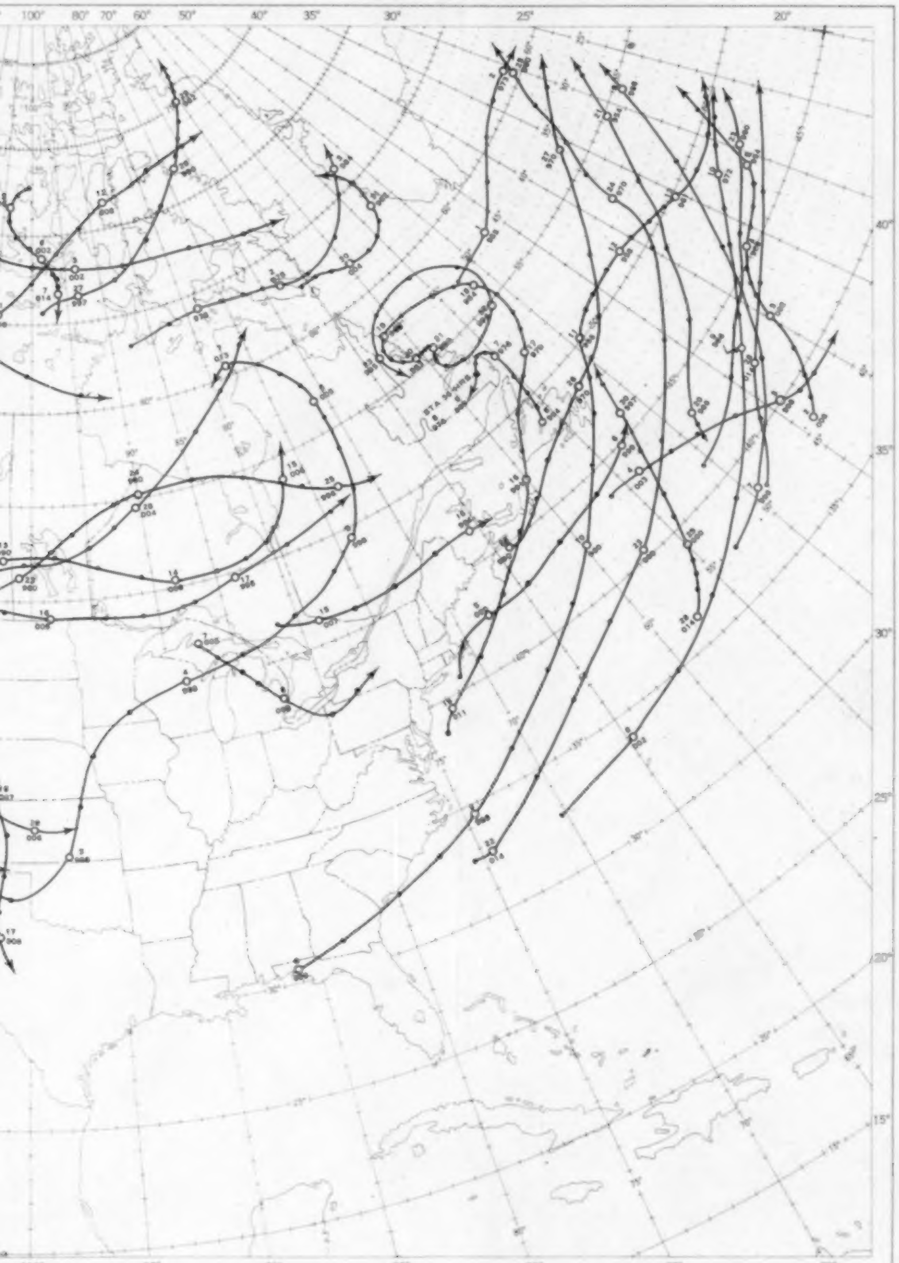
above circle indicates date, figure below, pressure to nearest millibar. position of stationary center for period shown. Dashed line in track rs which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea



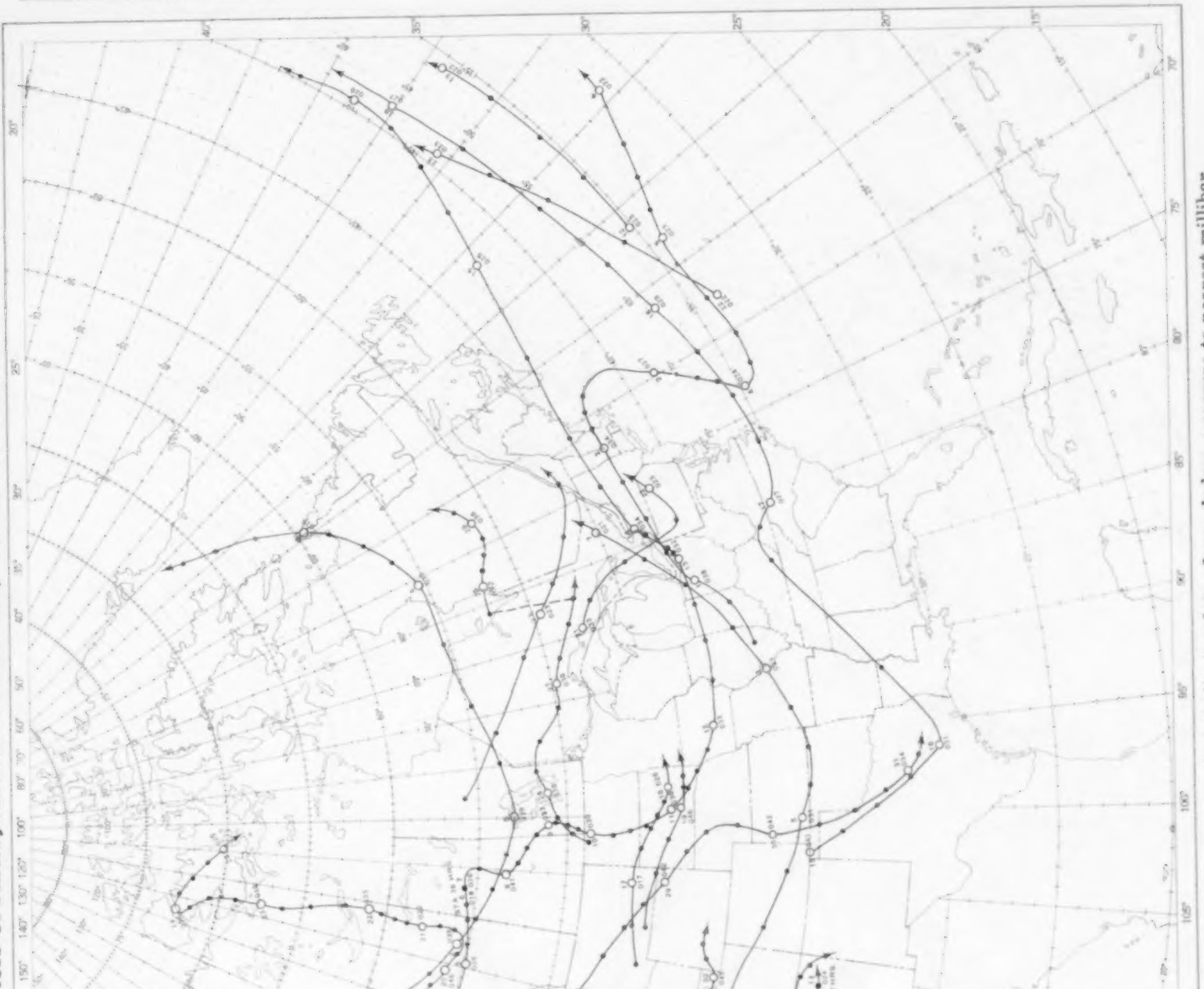
Circle indicates position of center at 7:30 a. m. E. S. T.

s at Sea Level, December 1955. (Corrected)



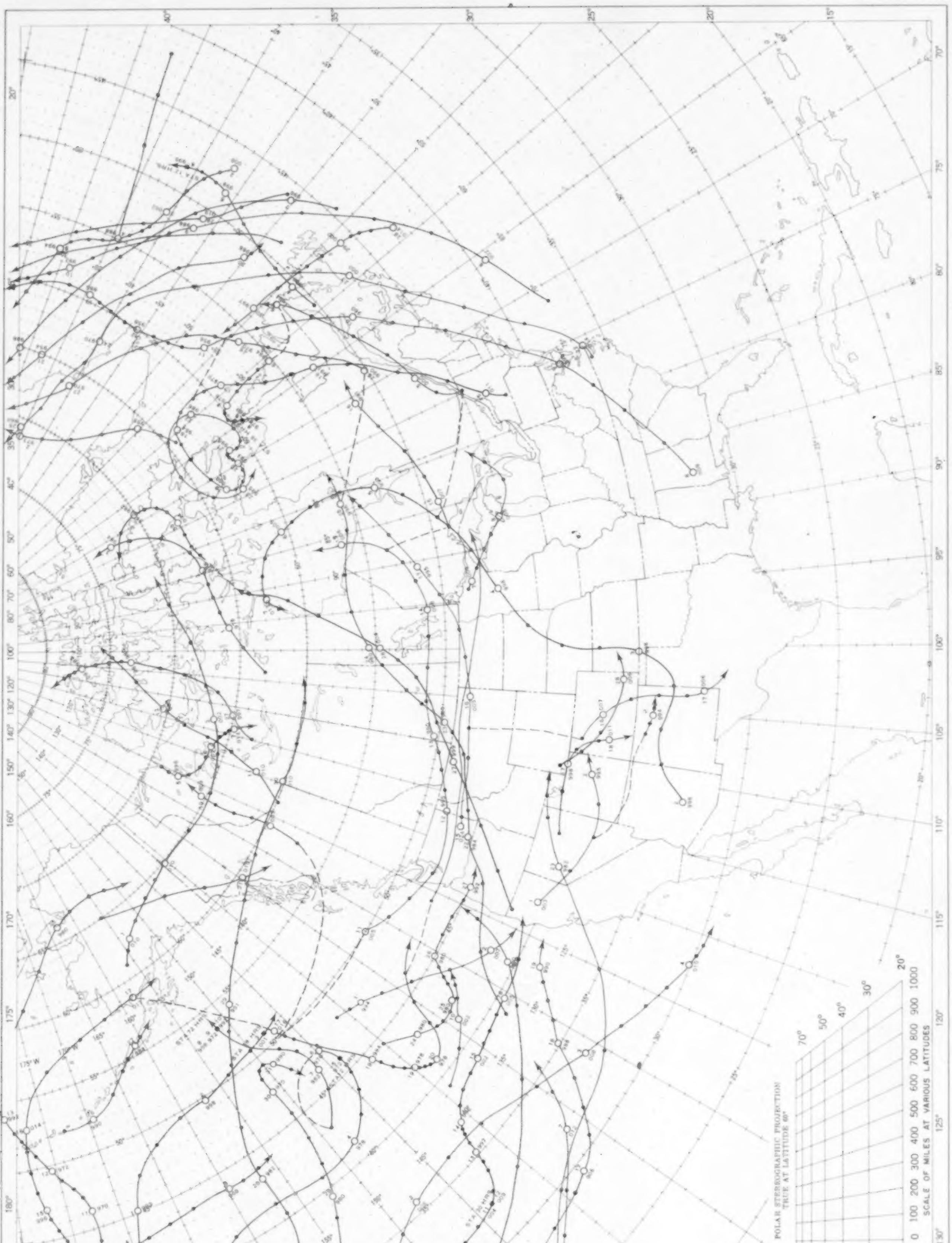
E. S. T. See Chart IX for explanation of symbols.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, December 1955.



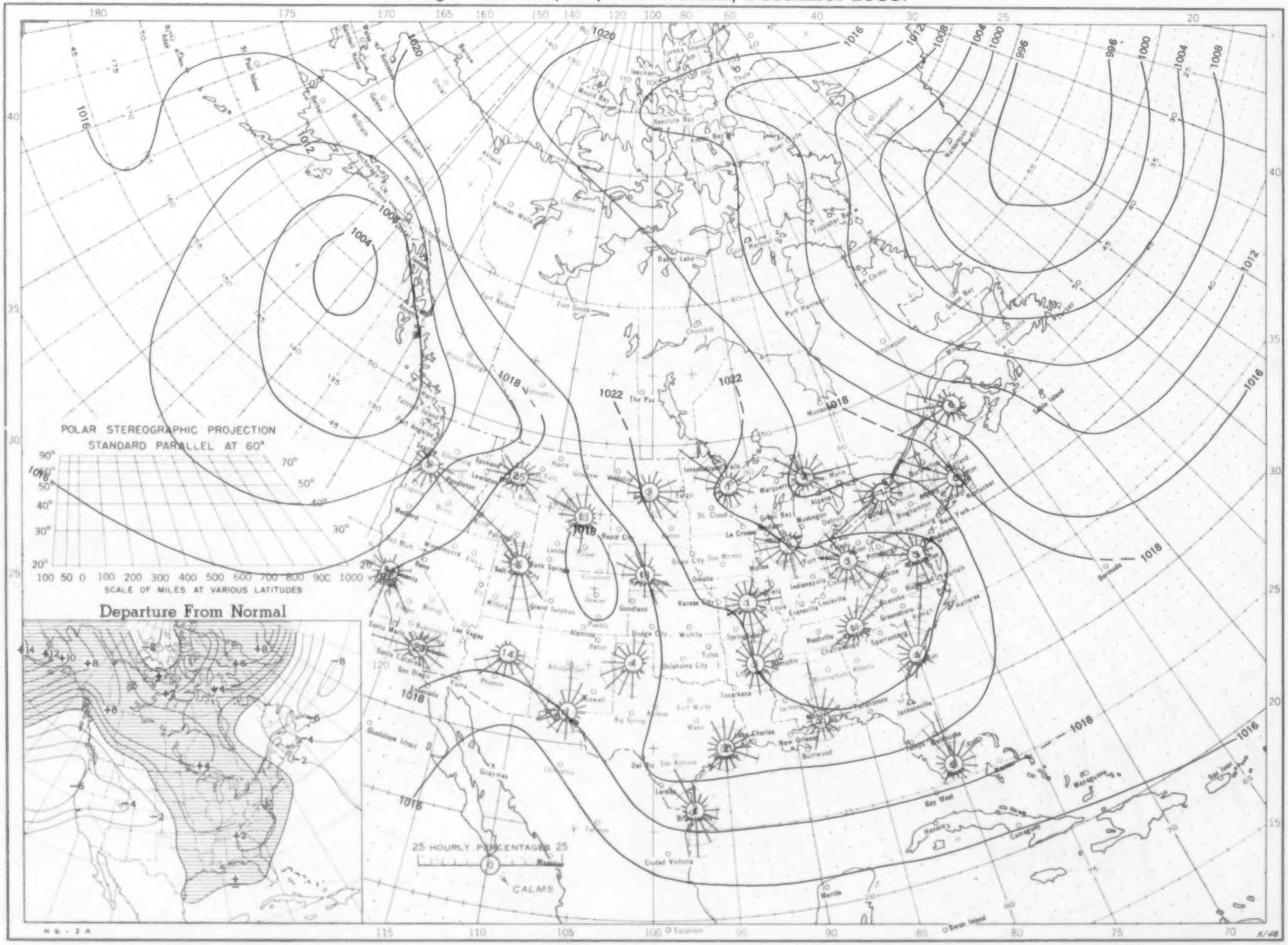
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, December 1955.



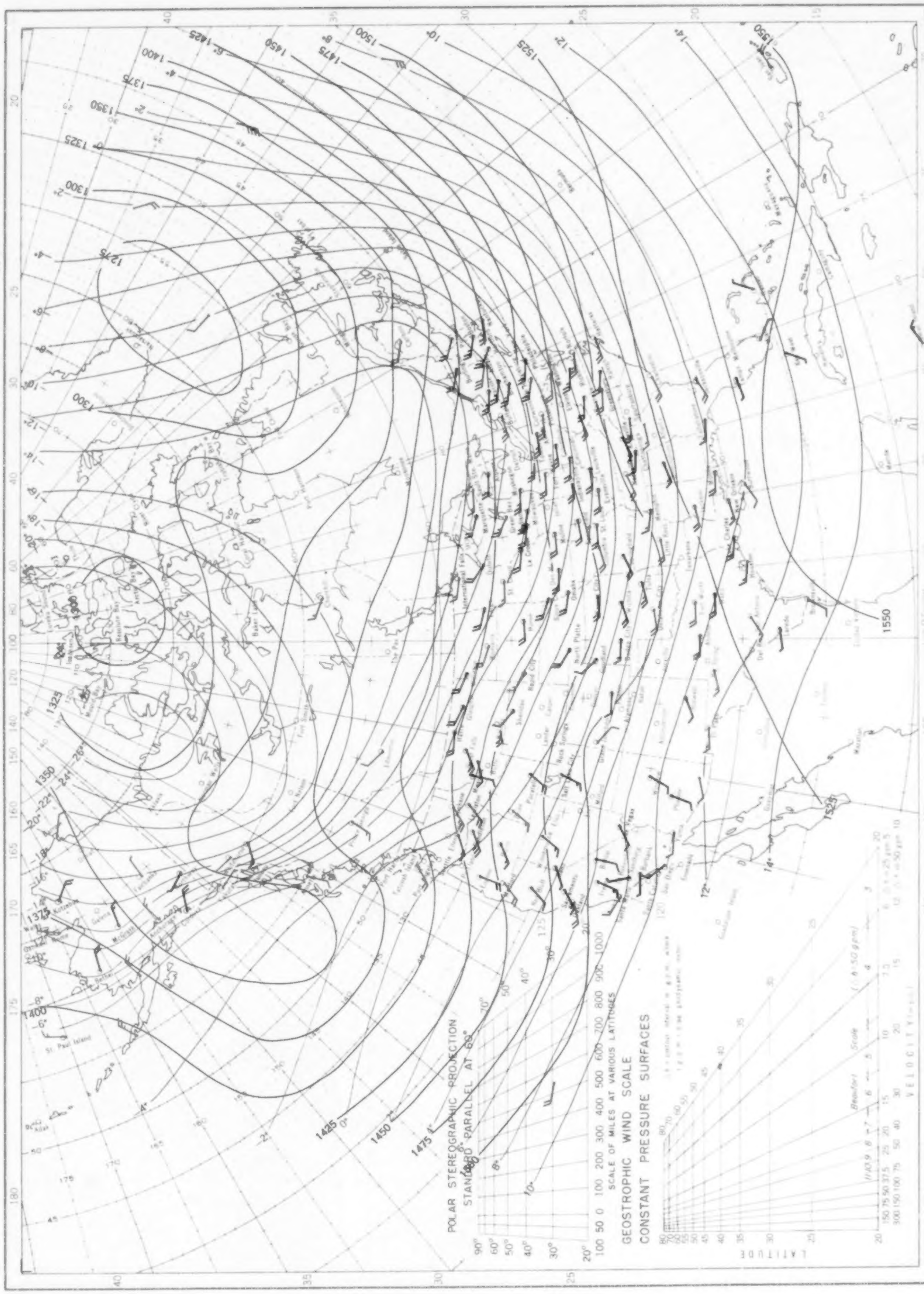
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, December 1955. Inset: Departure of Average Pressure (mb.) from Normal, December 1955.



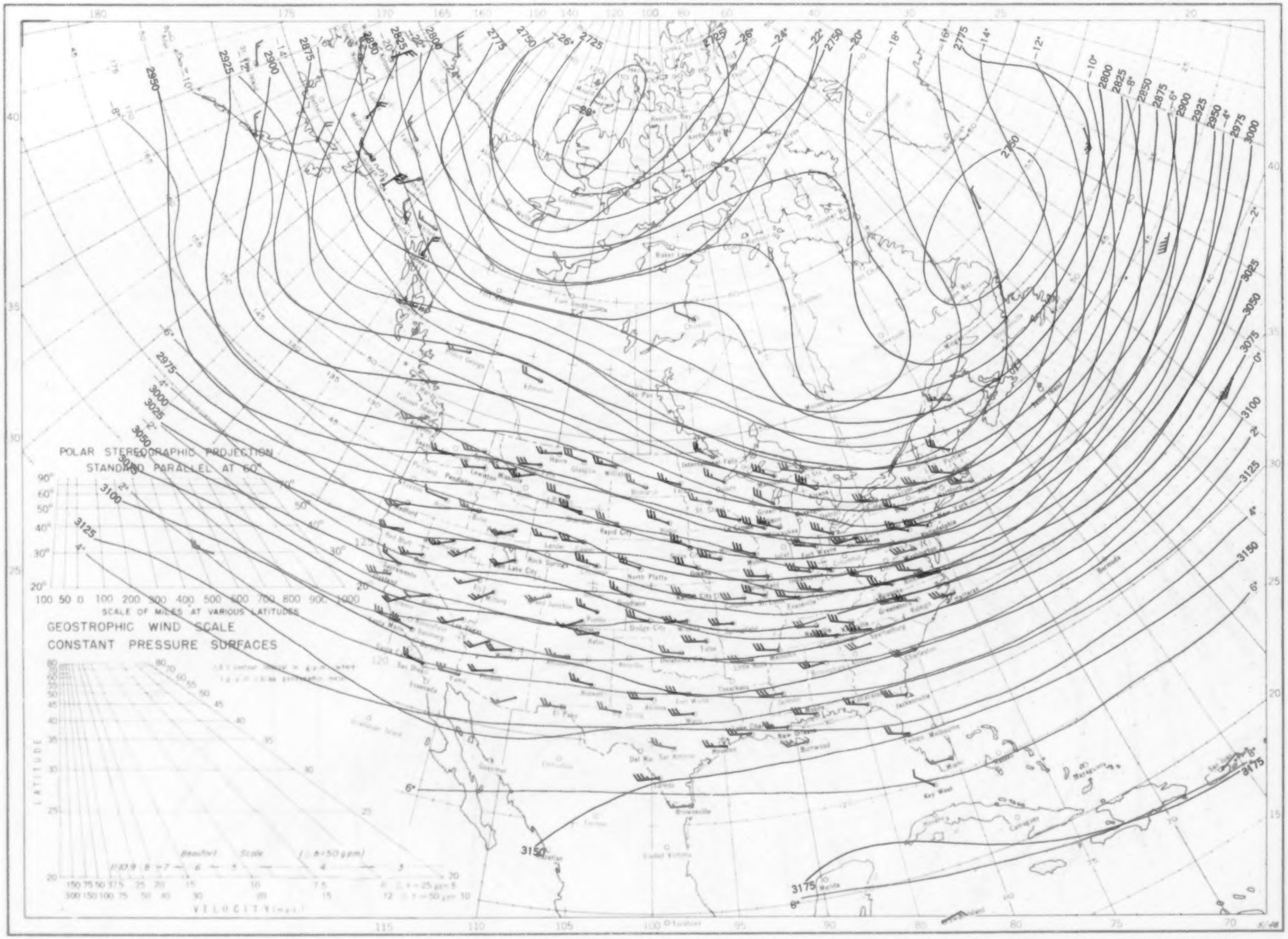
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), December 1955.



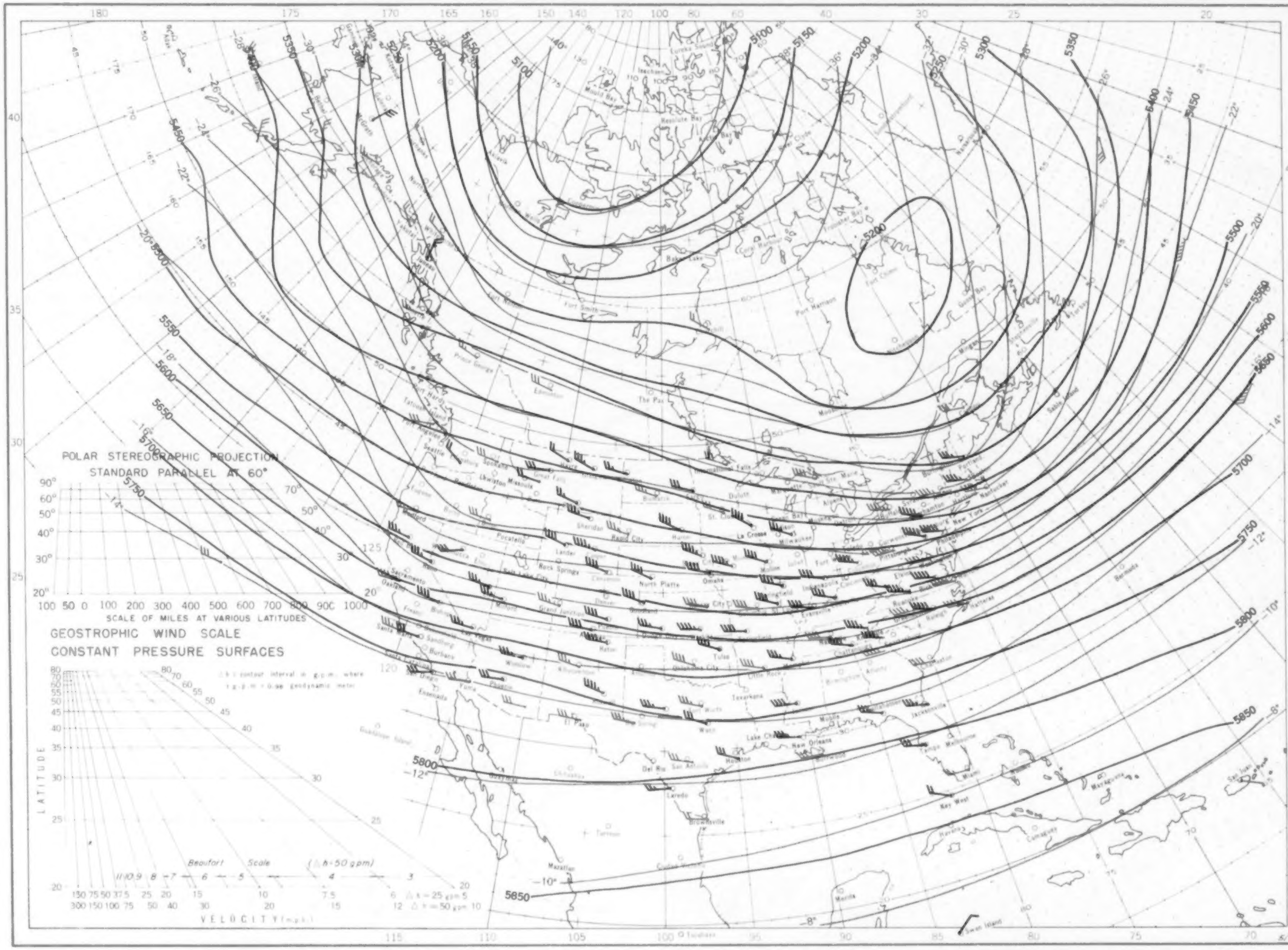
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g. p. m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), December 1955.



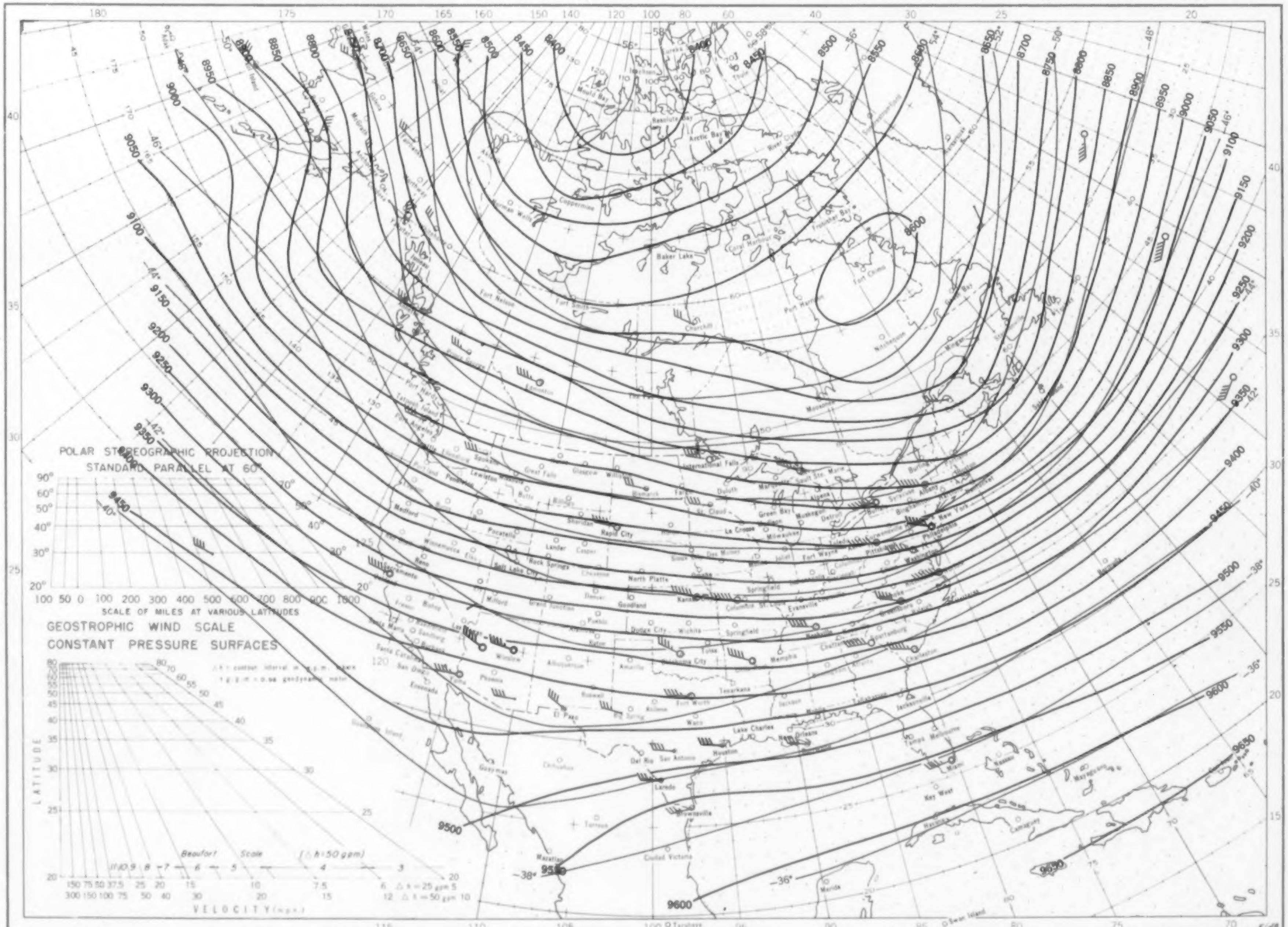
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), December 1955.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), December 1955.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

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(Continued from inside front cover)

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